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VEIN FORMATION AT PORCUPINE, ONTARIO.

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INTRODUCTION.

IN the Porcupine area of Ontario, extensive underground workings afford an excellent opportunity for the study of the mode of formation of the gold-bearing quartz veins and lodes. The occurrence and character of these deposits have been described by numerous observers, among whom may be mentioned Hore,[1] Robinson,[2] Spurr,[3] Burrows,[4] Dougherty,[5] Graton and McKinstry,[6] and Bain.[7]

[1] R. E. Hore: On the Origin of the Porcupine Gold Deposits. Can. Min. Jour., vol. 34, pp. 548–551, 1913.

[2] H. S. Robinson: Geology of the Pearl Lake Area, Porcupine District, Ontario. ECON. GEOL., vol. 18, pp. 753–771, 1923.

[3] J. E. Spurr: The Gold Ores of Porcupine, Ontario. Eng. & Min. Jour., vol. 116, pp. 633–638, 1923.

[4] A. G. Burrows: The Porcupine Gold Area. Ont. Dept. Mines, vol. 33, part 2, 1924.

[5] E. Y. Dougherty: Mode of Formation of Porcupine Quartz Veins. ECON. GEOL., vol. 20, pp. 660–670, 1925. *Idem.*, vol. 21, pp. 612–619, 1926. Replacement of Aluminous Rocks. Eng. & Min. Jour., vol. 122, p. 380, 1926.

[6] L. C. Graton and H. E. McKinstry: Outstanding Features of Hollinger Geology. Can. Inst. Min. & Met., Bull. 249, 1933.

[7] G. W. Bain: Wall-rock Mineralization along Ontario Gold Deposits. ECON. GEOL., vol. 28, pp. 705–743, 1933.

During the summer of 1932 the writer examined the vein systems in all the producing mines in the area. His conclusions with respect to the mode of formation of the veins differ from those expressed by previous writers chiefly in the emphasis he would place on open-space filling as opposed to replacement, and on intra-vein shearing and fracturing during the deposition of the vein matter.

The writer wishes to acknowledge his indebtedness and extend his thanks to the following officials and geologists of the mining companies operating in the area for the information and facilities placed at his disposal: W. C. Ringsleben, L. C. Graton, and H. E. McKinstry at the Hollinger mine; H. G. Skavlem and G. B. Langford at the McIntyre mine; J. G. McCrea and R. Murphy at the Dome mine; J. Reddington and H. J. C. Conolly at the Coniaurum mine; E. Y. Dougherty and W. Hamilton at the Vipond mine; and M. Knutson and R. V. Neily at the Buffalo-Ankerite mine.

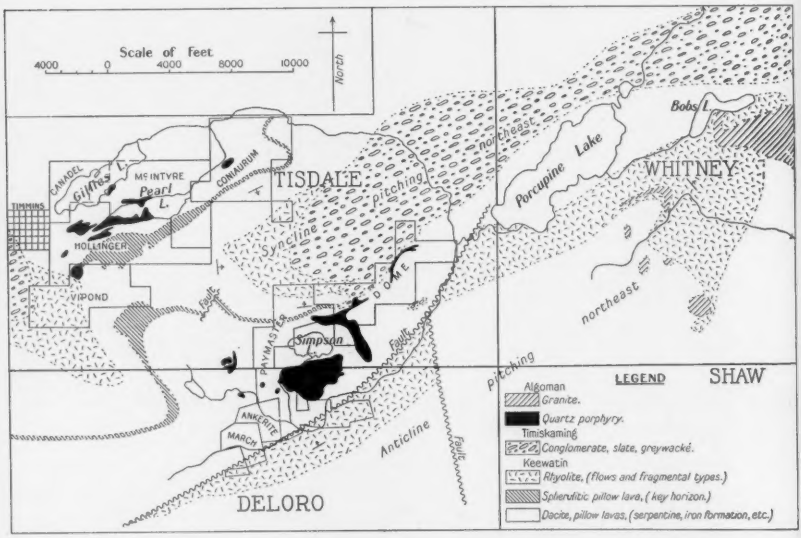

FIG. 1. Generalized geological map of the producing section of the Porcupine area.

GENERAL AND STRUCTURAL GEOLOGY.

The general geology and structure of the Porcupine area have been described by the late Dr. A. G. Burrows, of the Ontario Department of Mines. For more complete information on these subjects the reader is referred to his report.[8]

All the consolidated rocks in the Porcupine area are pre-Cambrian in age. The oldest group, known as the Keewatin, consists of a thick, orderly succession of dacite and basalt flows. These rocks are overlain by a group of acid volcanics consisting of rhyolite flows and rhyolitic agglomerate, tuff, and breccia. This group has been tentatively classified as upper Keewatin. In the central part of the area the acid fragmental rocks are overlain by conglomerate, graywacke, and slate of Timiskaming age. The lavas and sediments were extensively folded, and bodies of quartz porphyry were intruded along lines of structural weakness. These porphyry intrusions are believed to be related to the batholithic invasions of Algoman granite that occurred to the south and west of the Porcupine area. Further deformation, consisting chiefly of shearing and fracturing, followed the porphyry intrusions and gave rise to the open spaces in which the gold-quartz veins were subsequently deposited. Igneous activity was brought to a close with the introduction of diabase dikes, which cut the quartz veins as well as all the older rocks. The pre-Cambrian rocks now present a deeply eroded surface that is partially obscured by glacial drift.

Within the productive section of the area, the Keewatin and Timiskaming rocks form a synclinal structure, which pitches at a low angle to the northeast. Most of the folding and tilting is thought to have occurred prior to the intrusion of the porphyry bodies. Following these intrusions, differential movements took place along the margins of the syncline. During this deformation the porphyry bodies, located along the rim of the syncline, behaved as buttresses and major zones of weakness developed along their margins, especially where these face toward the axial plane of the syncline. The porphyry, greenstones and sediments

[8] *Op. cit.*

within these zones were intensely sheared and, as compression gave way to tension, fractures and open spaces developed irrespective of differences in texture, structure and composition. The principal shear zones are nearly vertical, but their axes pitch at an angle of 50°–55° toward the east. Beyond or away from the through-going shear zones the rocks are less disturbed and differential movements were confined to minor planes of weakness such as flow contacts, sedimentary horizons between flows, incompetent beds or flows, and dragfold surfaces. In still more remote and massive portions of flows, sedimentary beds, or porphyry bodies, these disturbances gave rise to short tension-cracks that strike at an angle to the principal planes of shearing.

The close association of important vein systems with bodies of quartz porphyry led to the belief that the mineralization was genetically related to these intrusions and that all contacts between quartz porphyry and greenstones or sediments constituted favorable ground for prospecting. Considerable underground exploration has been undertaken and directed on this assumption. Most observers now agree that the influence of the quartz porphyry bodies has been physical and not genetic and that structural deformation has been of paramount importance in determining the location and extent of the vein systems. The writer believes that the mineralization was related to and followed closely after the batholithic intrusions of Algoman granite and allied rocks.

VEIN STRUCTURE.

The veins, although similar in mineral content, differ widely in their structural or physical aspects. In the writer's opinion, this diversity in structure may be ascribed to the character of the open spaces created by shearing and fracturing prior to and during the introduction of the vein matter. The simplest structure is that in which the vein matter has been confined to a single relatively straight fissure. More complex vein patterns arise through branching and the development of braided structures. Some of the ore bodies consist of numerous parallel or branching stringers separated by strips or blocks of mineralized wall rock.

These deposits may be more accurately described as composite veins, stockworks, or lodes.

On the basis of structure, the veins may be classified as follows:

1. Single, more or less tabular veins.
2. Branching and braided veins.
3. Curved, sinuous, or contorted veins.
    a. Those that occur in spaces created by drag-folding.
    b. Those that occupy spaces developed across the strike of schists or sediments as a result of fracturing accompanied by differential movements along the planes of schistosity or stratification.
    c. Those that alternately pinch and swell along the strike, resembling a string of sausages.
    d. Those that occur along folded flow contacts, and resemble saddle reefs.
    e. Those related to shears that intersect relatively massive rocks, and are shaped like pothooks, or S's or reverse S's (Fig. 3). In each instance the stem of the pothook lies along the plane of maximum shearing, whereas the hooks have developed in the adjoining less disturbed rock where tensional stresses prevailed.
4. Some veins have been intersected by transverse fractures, which have been filled by later vein matter (usually referred to as ladder structure).
5. Composite veins, stockworks, and lodes.
    a. Those made up of parallel veins separated by strips of wall rock.
    b. Those made up of a plexus or network of veins separated and bordered by wall rock.
    c. Those in which the veins occur *en échelon*. In the Hollinger mine, lodes of this type consist of a series of east-west veins, each successive vein lying to the northeast of that immediately preceding it.
6. Pyritic ore bodies of irregular outline.

Some of the highly curved or sinuous vein structures have been interpreted by various observers as being due to folding subsequent to the deposition of the vein filling. On close examination, most of the evidence appears to be decidedly opposed to this view. In the writer's opinion these structures are the result, not of selective replacement, but of selective mechanical deformation that took place prior to, or during, the deposition of the vein matter.

AGE RELATIONSHIPS OF VEINS.

A study of the vein systems has led the writer to the conclusion that there has been one major [9] period of mineralization in the area. The deposition of vein matter is thought to have been a continuous process, although, from beginning to end, the chemical composition of the mineralizing solutions undoubtedly underwent considerable change. There is, however, cogent proof that structural readjustments occurred at intervals during the process of vein formation. On this basis it is possible to subdivide the principal period of mineralization into at least three stages, as follows:—

First stage: The original or earliest fractures were occupied by veins in which tourmaline is a conspicuous if not predominant constituent. The deposition of pyrite (or pyrrhotite) and ankerite began at this time, but quartz is sparingly present.

Second stage: This stage was marked by periodic structural readjustments. Pre-existing fractures, including those occupied by the tourmaline-bearing veins, were re-opened and greatly enlarged. Other fractures were developed or enlarged by each successive movement. Deposition of vein matter took place as and when open spaces became available. Quartz was introduced in great abundance during this stage and, at the close, the veins approximated their present size.

Third stage: This stage was marked by local fracturing of veins previously formed, usually with the development of "ladder" structure, and by the development of new fractures in outlying portions of the disturbed zones. Calcite is a characteristic constituent of these late veins.

Although evidence of all three stages can seldom be found in a single vein, there are many veins that exhibit two of the stages described above. The second stage was by far the most important, as probably eighty-five per cent of the total vein-filling was introduced during this stage.

WALL-ROCK ALTERATION.

The original structure, texture, and mineral composition of the rocks in the Porcupine area have been considerably modified

[9] The ferrodolomite zones in the greenstones and certain ankerite veins are believed to have been formed during an earlier period of mineralization.

by regional metamorphism. This alteration has been accentuated locally by shearing movements, by vein-forming solutions, or by a combination of both. Wall-rock alteration is most pronounced in the vicinity of veins formed during the early stages of mineralization. Toward the close of the period of vein formation such alteration was almost if not entirely lacking.

The influence of the vein-forming emanations can be recognized, in some instances, by the bleached appearance of the wall rocks immediately adjoining the veins. This condition occurs most commonly where the wall rock consists of highly chloritic greenstone. In order to throw some light on the chemical changes involved, samples were taken of fresh and altered wall rocks (dacite, basaltic pillow lava, quartz porphyry) in the vicinity of veins along which alteration was most apparent. These samples were submitted to the Provincial Assay Office, Toronto, where the analyses of Table I were made by W. F. Green.

The analyses of Table I show that: (*a*) the greenstones have been more profoundly affected by the vein-forming emanations than the quartz porphyry; (*b*) alteration of the wall rocks has involved conspicuous gains in sulphur and potash and a marked loss of silica; (*c*) the silica loss is largely dependent upon the amount of sulphur introduced; (*d*) the alumina content has remained practically unchanged; (*e*) intense pyritization is accompanied by a decrease in the carbonate content. Mineralogically the principal changes have been the alteration of the feldspars to sericite, carbonate, and quartz, of the chlorite and other ferromagnesian minerals to carbonate, pyrite, and quartz, and of the carbonate to pyrite. The primary quartz content of the rocks has remained unchanged.

The wall rocks, especially the greenstones, had been extensively carbonated prior to the introduction of the vein-forming gases and solutions. Under the influence of these emanations, further carbonitization of the wall rocks took place; sericitization became more pronounced; and the introduction of sulphur resulted in the formation of pyrite and the removal of silica. These changes, although increasing the density of the wall rock, appear to have

TABLE I.

ANALYSES OF FRESH AND ALTERED WALL ROCKS.

Chemical Composition.	1 Dacite.		2 Pillow Lava.		3 Quartz Porphyry.	
	A Fresh.	*B* Altered.	*A* Fresh.	*B* Altered.	*A* Fresh.	*B* Altered.
	%	%	%	%	%	%
SiO_2	45.83	37.03	38.97	27.30	63.53	61.56
Al_2O_3	12.88	15.53	11.24	13.89	15.68	18.74
Fe_2O_3	0.90	1.10	0.20	nil	1.30	trace
FeO	9.73	(5.02)*	15.81	3.20	4.08	0.87
CaO	6.03	9.27	6.84	7.27	1.19	2.48
MgO	6.52	5.04	3.11	2.39	1.08	1.18
K_2O	1.25	2.18	0.76	2.29	2.07	4.00
Na_2O	2.38	3.48	3.88	2.87	4.27	2.66
H_2O	2.70	1.07	0.58	1.30	1.02	1.85
CO_2	10.58	13.77	16.80	9.54	4.42	3.83
TiO_2	1.10	0.85	1.19	1.47	0.15	0.41
P_2O_5	0.11	0.08	0.32	0.37	0.12	0.18
MnO	nil	0.19	0.02	0.02	0.13	trace
FeS_2 (pyrite)	0.17	10.76	0.23	28.54	0.47	2.89
	100.18	100.35	99.95	100.45	99.51	100.65
S. G.	2.860	2.935	2.924	3.415	2.760	2.752
Gold, oz. per ton	——	0.077	——	2.42	——	nil
" value ($20.67 per ton)	——	$1.60	——	$50.00	——	nil

* Included in pyrite.

1. Samples from the walls adjoining a branch of No. 2 vein, 550-foot level, Hollinger mine (Fig. 7).
   A. Comparatively fresh dacitic greenstone, typical of the wall rock several feet from the vein. The microscope shows this to be composed chiefly of chlorite, carbonate, and remnants of plagioclase, together with a little orthoclase, sericite, and primary quartz.
   B. Highly altered, bleached phase of "A," immediately adjoining the vein. This consists chiefly of carbonate, pyrite, and sericite, with some quartz (both primary and secondary).
2. Samples from a stope on No. 44 vein above the 300-foot level, Hollinger mine.
   A. Comparatively fresh, dark-gray pillow lava several feet from the vein.
   B. Highly altered, pyritized phase of "A," immediately adjoining the vein.
3. Samples taken in the vicinity of No. 218 vein, 200-foot level, Hollinger mine.
   A. Sample typical of the quartz porphyry mass, taken 30 feet from the vein.
   B. Waxy phase of "A," from the walls immediately adjoining the vein.

taken place without appreciably affecting its volume. In some instances ferrous iron and magnesia appear to have been removed from the wall rocks along with silica. These constituents were

probably re-deposited in the vein filling as ankerite, pyrite, and quartz.

The development of pyrite appears to have been dependent upon the amount of sulphur contributed by the mineralizing emanations and upon the volume of ferrous iron present in the wall rock in the form of chlorite or other ferromagnesian minerals. In some instances, pyritization of the greenstones has been so complete that practically all the carbonate and ferromagnesian constituents have been used up and the resulting rock consists of a dense, hard mixture of pyrite, sericite, and silica. From an economic standpoint pyritization of the wall rocks is of great importance, as a large proportion of the gold is intimately associated with this sulphide and was to some extent deposited contemporaneously with it.

Hydrothermal alteration, especially of the greenstones (propylitization), imparts a bleached appearance to the wall rock. This loss of color is due to the decomposition of the chlorite or other ferromagnesian minerals. In spite of this change the wall rock never completely loses its physical identity. It is usually sharply separable from the vein matter, although the abruptness with which the change takes place depends on the physical condition of the wall rock, the contacts being clear-cut where the wall rock is massive and less well-defined where the wall rock is schistose.

VEIN ENLARGEMENT.

It is generally conceded that shearing and fracturing provided the initial open spaces or channels in which the circulation of vein-forming solutions began. Although some of these fractures or the veins in them have not been affected by later movements, there is unmistakable evidence in the majority of veins that the original fissures have been greatly enlarged during the process of vein formation. There exists, however, some difference of opinion as to how this enlargement was accomplished. The following theories are those most frequently advanced:

1. The vein walls were forced apart by mineralizing solutions or ore magma injected under tremendous telluric pressure.

2. Separation of the walls was due to the force exerted by crystallization of the constituents in the vein filling.

3. Enlargement was accomplished by a process of replacement in which wall rock was removed and vein matter substituted in its place.

4. The original fissures were enlarged by mechanical deformation involving, (*a*) one relatively rapid movement, followed by deposition of vein matter; or (*b*) a single, slow, continuous movement, the gradual creation of open spaces being accompanied by simultaneous deposition of vein matter; or (*c*) a series of movements, each of which provided additional vein space and involved brecciation of the wall rocks and/or of the vein matter previously deposited. It is assumed that the infiltration of vein-forming solutions was continuous throughout.

There is little evidence to indicate that injection of vein constituents under telluric pressure or the force exerted by growing crystals played an important part in producing vein enlargement. Most observers are probably inclined to the view that the veins attained their present size through a combination of open-space filling and replacement. They assume that vein deposition began in open spaces formed originally by structural deformation; that such spaces were relatively narrow; and that vein enlargement was brought about by replacement of the wall rock. In the writer's opinion, the replacement of wall rock by vein matter played an insignificant part, if any, in vein enlargement. It is his belief that enlargement was accomplished chiefly by physical or structural readjustments occurring at intervals during the period of vein deposition.

Enlargement by Replacement.—Some observers are of the opinion that alteration of the wall rocks adjoining a vein is evidence that replacement of wall rock by vein matter has been an important factor in the formation and enlargement of the vein. The presence of wall rock inclusions (so-called remnants of replacement) within the vein matter seems at first glance to afford further proof that such an interchange has taken place. These points are discussed in the following paragraphs.

As a result of hydrothermal alteration, the feldspars, chlorite, and other ferromagnesian minerals originally present in the wall rocks have been decomposed and their constituents re-arranged and re-crystallized to form sericite, carbonates, pyrite, and quartz.

Where such alteration has been most intense, even the carbonates have been replaced by pyrite. As a result, the percentage of quartz has been relatively increased, and this gives the impression that the wall rock has been silicified by the addition of quartz from the vein-forming solutions. The analyses given on a previous page clearly show that such is not the case and that silica has been removed from, rather than added to, the wall rocks. Thus, what appears to be an actual increase in the silica content is, in reality, only a relative increase in the quartz content brought about by the development of pyrite at the expense of the carbonates or ferromagnesian minerals in the wall rocks. Since silica has actually been removed from the wall rocks, it is evident that any enlargement of the veins due to substitution of vein quartz for wall rock must have been confined to and completely effected at the wall rock surfaces immediately in contact with the vein-forming solutions. Since the percentages of sericite, albite, and other aluminous minerals in the vein matter are too small to account for all the alumina in the replaced wall rock, it is evident that substitution of vein matter for wall rock would involve an actual loss of alumina. The analyses show, however, that the alumina content of the wall rock has remained practically unchanged, even where alteration has been most intense.

It would appear, therefore, that the presence of pneumatolytic or hydrothermal alteration in the wall rocks adjoining a vein cannot be used as evidence of replacement of wall rock by vein matter, that is, of vein enlargement by replacement. If such encroachment has occurred, the chemical interchange of constituents must have been confined to and accomplished at wall-rock surfaces immediately in contact with the vein-forming emanations.

As evidence of vein enlargement by replacement, advocates of this theory point (*a*) to the presence in the vein filling of "floating" inclusions or relics of country rock, and (*b*) to the frayed, feathery margins of many of these inclusions. As there is no positive evidence that the vein filling has encroached on the wall rock, one is justified in assuming that unsupported inclusions were

not separated from the walls by any process of replacement. As stated elsewhere, the writer believes that such inclusions originated through periodic fracturing while deposition of vein matter was in progress. He has repeatedly observed that inclusions within the veins possess the same structure and texture as the adjoining wall rocks. Furthermore, where the wall rocks are massive and even-grained, the margins of the inclusions are smooth, straight, and clear-cut; where the wall rocks are schistose and contorted, the boundaries of the inclusions are ragged, uneven, and sinuous. In the writer's opinion, the wisp-like character and frayed, feathery margins exhibited by some of the so-called relic inclusions

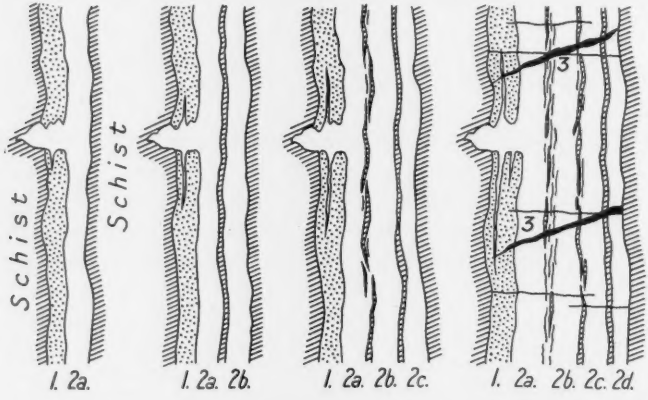

FIG. 2. Diagrams illustrating (*a*) age relationships of veins and (*b*) vein enlargement by mechanical deformation. 1, tourmaline-bearing vein 2–*a*, *b*, *c*, *d*, successive generations of quartz. 3, quartz-calcite veins, ladder structure.

are the result of intra-vein shearing and fracturing of wall-rock fragments that were probably schistose to begin with.

Enlargement by Structural Deformation.—The Porcupine area has been extensively affected by regional deformation. In the producing section of the camp, the greenstones and sediments have been folded into a synclinal structure, which pitches to the northeast. The deforming stresses were of such intensity that

rupturing took place, especially near the margins of the porphyry intrusions that occur along the rim of the structure. The stresses were relieved by differential movements along these planes of weakness; the adjoining greenstones and sediments were sheared and fractured; and, as compression gave way to tension, the fractures and open spaces gradually increased in size. The circulation of vein-forming solutions probably began shortly after channelways became available and continued until the structural readjustments were almost completed.

It is evident from a study of vein relationships that structural readjustments occurred at intervals during deposition of the vein filling. Recognition of this fact has made possible a subdivision of the period of vein formation into three stages, as outlined on a previous page. Mechanical deformation and introduction of vein matter were most extensive during the second stage. Vein enlargement, in most instances, was not accomplished by a single movement but by a series of movements, each of which increased the length, width, and depth of the pre-existing fissures. The displacement was chiefly horizontal in a direction at right angles to the strike of the original fracture (*i.e.* largely tensional). To a lesser extent, the movements involved vertical displacement (throw) and horizontal displacement parallel to the strike of the vein. Each movement probably caused some brecciation of vein matter previously deposited, local shattering and shearing of wall-rock inclusions in the vein filling, and loosening of additional fragments from the walls. Deposition of vein matter in the newly created spaces is thought to have followed each movement.

Some of the lode deposits are made up of closely spaced, parallel veins separated by and alternating with bands or slab-like partings of country rock (Fig. 4). Vein structures of this type commonly afford evidence of enlargement by mechanical deformation. In most cases, the parallel fractures (*2a, b, c, d,* Fig. 2) appear to have been formed by one and the same movement and to have been filled simultaneously by vein matter of identical appearance and composition. In some lodes, the banded structure appears to be due to repeated fracturing and vein deposition.

In such instances, it is believed that the original fissure was occupied by vein matter that became " frozen " or firmly attached to the walls. In response to structural readjustments (chiefly tensional), rupturing occurred, not along the closely knit vein contacts, but along a parallel plane in the rock adjoining one side of the vein (Fig. 2). In this way a selvage, sheet or slab of country rock, " frozen " to the vein matter (*2a*) on one side, was split from the wall. The space thus formed was then occupied by fresh vein matter (*2b*). Repetition of this process (*2c, d*) would give rise to a banded lode.

The majority of veins in the Porcupine area contain inclusions of country rock. Where the adjoining rocks are schistose, the inclusions consist of laminated bands, sheets, or strips arranged, as a general rule, parallel to the vein walls (Fig. 5). Where the wall rocks are massive the inclusions mostly consist of angular, polygonal blocks, slabs, or fragments having no very definite orientation (Fig. 8). It may be safely assumed that many of these inclusions were loosened or broken from the walls when the original fissures were formed; that they were supported at points of contact with the walls or with each other; and that the vein filling was deposited in any available cracks or interstices. There are, however, many inclusions that are wholly surrounded by, or " floating " in, vein matter, and any theory of vein enlargement must adequately account for their presence. Spurr assumes that the viscosity or supporting power of the mineralizing solutions was such that the inclusions were sustained in suspension until the vein matter consolidated. If this were so one would expect to find that, with the migration of the vein-forming solutions, some of the inclusions had been transported from their original positions and that some of the fragments were foreign to or unlike the adjoining wall rock. No such evidence was found. Other observers believe that these " floating " inclusions are remnants isolated from the walls by replacement. In the writer's opinion the weight of chemical evidence is opposed to this view. Furthermore, he is confident that the physical and structural criteria advanced in support of such replacement can be accounted for by mechanical deformation.

3 4 5

FIG. 3. "S" or hook-shaped quartz veins, 2,000-foot level, Hollinger mine.

FIG. 4. Banded structure typical of quartz lodes in schistose rocks. No. 16 vein, 2,500-foot level, McIntyre mine.

FIG. 5. Quartz vein containing sheets and film-like inclusions of schistose wall rock. This structure is believed to be due to intra-vein shearing and fracturing during vein deposition. No. 3 vein, 1,625-foot level, McIntyre mine.

In the writer's opinion, inclusions that are now entirely surrounded by vein matter were at one time loosely attached to or supported by the walls. Vein matter was introduced and solidified in the main fissure and in the cracks that partially surrounded the loosened fragments. Subsequent structural readjustments reopened the vein and widened the original fissure in such a way that fragments that were partially imbedded in and held in place by solid vein matter were severed or plucked from the walls. With the introduction of fresh vein filling into the newly formed spaces, the fragments became completely surrounded by vein matter.

Instances have been observed of so-called unsupported inclusions of wall rock that have subsequently been penetrated by veinlets of quartz. In other instances, inclusions have been completely severed into segments that have been offset and surrounded by quartz. One might suspect that this brecciation of "floating" inclusions was due to post-vein movements, but careful examination shows that such is not the case. A plausible explanation seems to be that both vein filling and inclusions were cracked or broken by intra-vein movements and that the fractures so formed were subsequently occupied by quartz similar in color and texture to that previously deposited. Although the margins of the fractures are in places marked by faint cracks, as a rule the later quartz is so intimately intergrown and blends so completely with the earlier quartz that no perceptible surface of demarcation remains. In places, the presence of vugs indicates that such fractures have been incompletely healed or filled.

FIG. 6. Tourmaline-bearing vein (right) cut (see penknife) by quartz-ankerite vein (white). No. 95 vein, 3,350-foot level, Hollinger mine.

FIG. 7. Bleached and altered dacitic wall rock adjoining No. 2 vein, 550-foot level, Hollinger mine. Analyses 1–A and 1–B, Table I, were made from samples obtained here.

FIG. 8. Brecciated structure typical of veins in massive greenstones. Note the sharp, angular outlines of the inclusions. 15th level, Dome mine.

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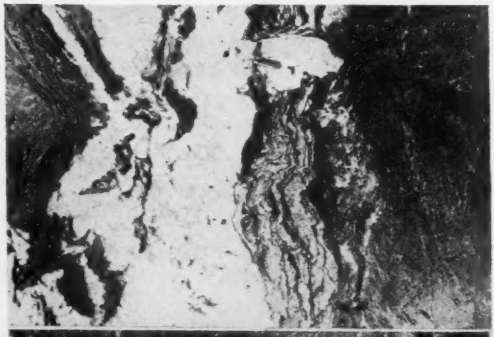

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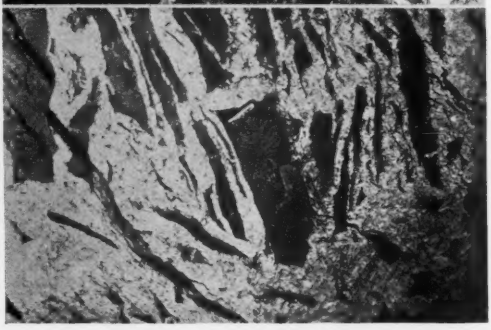

It is a matter of frequent observation that inclusions within the veins, whether they be massive or schistose, possess the same structure and texture as the adjoining wall rocks. If the inclusions are massive and even-grained, intra-vein fracturing produces sharp-cornered fragments with straight, smooth margins. If the inclusions are schistose, then further fracturing follows the foliation and gives rise to sheets, streaks, and wisps of schist, which are normally aligned parallel to the walls of the vein. When the folia are extremely thin or frayed they are generally bounded by vague, feathery edges that fade gradually into the surrounding vein matter. This condition is regarded by some observers as evidence of replacement, but, in the writer's opinion, it is simply due to the ease with which the schist inclusions split, in response to intra-vein movements, into extremely thin sheets.

Further evidence of structural deformation during vein deposition is afforded by microscopic study of the pyritized wall rocks. Where the wall rocks are schistose, the grains or crystals of pyrite are commonly partially surrounded by fringes composed of secondary silica and other products of wall-rock alteration. It is evident from the shape, disposition, and crystalline structure of these fringes that the pyrite crystals have been rotated from the position in which they were originally formed. As post-vein deformation within the ore zones has been confined to local faulting, it seems probable that the rotation of the pyrite crystals was brought about by shearing movements during the period of vein formation.

SEQUENCE OF MINERALIZATION.

Although the veins can be differentiated, in respect to relative age, on the basis of fracturing that occurred during the period of vein formation, the writer believes that mineralization was, nevertheless, a continuous process. It is evident from a study of the mineral content in veins of different age that there was a marked, but probably gradual, change in the composition of the mineralizing emanations during the period of vein formation. Tourmaline is characteristic of veins formed in the earliest stage

of mineralization, whereas calcite is typical of those formed toward the close of the vein-forming period. Pyrite (pyrrhotite at the Dome mine), ankerite, and quartz are the most "persistent" minerals in the veins. Gold deposition also took place during a relatively long interval. Deposition of such minerals as scheelite, albite, axinite, clinozoisite, sphalerite, galena, and the tellurides was restricted to much shorter intervals. The sequence in which the principal minerals were deposited is shown graphically in Fig. 9.

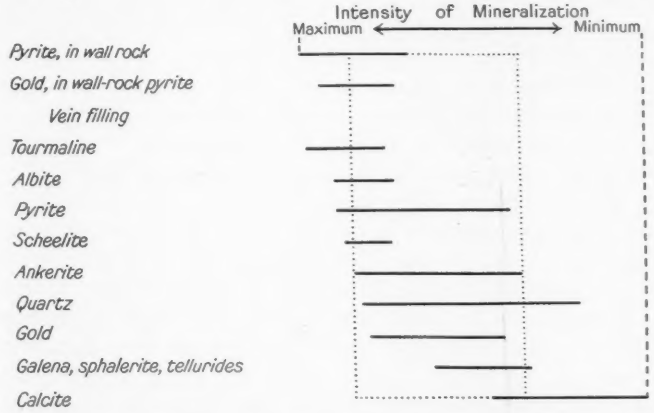

FIG. 9. Diagram showing sequence of mineralization.

In the writer's opinion, structural readjustments occurred periodically along the principal zones of shearing. These movements gave rise to a series of fractures developed roughly parallel to, and successively farther from, the planes of maximum dislocation. Deposition of vein matter took place as and when open spaces became available, the mineralization changing in character and diminishing in intensity progressively outward from the principal channelways. Open spaces within the zones of most intense disturbance received the earliest and most potent increments of vein matter (pyrite-tourmaline veins); slightly later, following

widespread fracturing, quartz-ankerite veins (mineralization of intermediate intensity) were introduced on a large scale; and finally, the most remote and last-formed fractures or portions of fractures were occupied by vein matter (quartz, calcite, anhydrite) characteristic of the closing phase of mineralization.

Studies conducted by Graton and McKinstry [10] at the Hollinger mine, and by G. B. Langford [11] at the McIntyre mine have shown that the principal areas of mineralization may be subdivided into an inner gold-bearing zone, in which the veins are largely of the quartz-ankerite type, and outer unproductive zones, in which quartz-calcite veins predominate. The writer believes that this zonal arrangement is related to the sequence of fracturing and to the variation in potency of the sulphur-bearing compounds in the vein-forming solutions. In discussing wall-rock alteration, attention was called to the fact that sulphur was the principal constituent contributed by the vein-forming solutions and that, in the development of pyrite at the expense of carbonates or ferromagnesian minerals in the wall rock, ferrous iron and magnesia were liberated. These constituents may have contributed to the formation of pyrite and ankerite in the vein filling. If such is the case, then the relative abundance of ankerite in the vein filling would be dependent, to some extent, on the volume and potency of the sulphur-bearing compounds in the vein-forming emanations and on the abundance of ferromagnesian constituents in the wall rocks.

Albite is one of the earliest minerals in the quartz-ankerite veins. When present, it generally occurs along the margins of the veins or about inclusions of wall rock. The deposition of this mineral may be related to hydrothermal alteration of wall rocks that are relatively rich in soda.

Axinite and clinozoisite occur chiefly in veins located on the fringe of the mineralized zones. These minerals appear to have been deposited when the sulphur content of the solutions had been reduced to a point where it was no longer capable of

[10] *Op. cit.*, p. 11.

[11] Oral communication.

liberating sufficient ferrous iron or magnesia from the wall rocks to form tourmaline.

ORE SHOOTS.

One cannot fail to be impressed, on inspecting the underground workings of the principal mines, by the large volume of vein matter which closely resembles the productive veins in appearance and mineral content, but in which the gold values are below commercial grade or absent. The reason for this unequal distribution of gold in the veins, i.e. for the presence or absence of ore shoots, is to be found in the factors that controlled vein formation. As has been previously pointed out, these factors were (*a*) structural and (*b*) chemical in character. The location, size, and shape of the open spaces occupied by the veins were determined by structural readjustments prior to and during the deposition of vein matter. The mineral content of the vein matter deposited in a particular open space and the extent and character of the wall-rock alteration would reflect and be dependent upon the chemical composition of the mineralizing emanations at the time the fracture was occupied. As gold deposition was confined to a certain duration of time in the period of mineralization, only fractures formed and wall rocks exposed during this interval would be penetrated by auriferous solutions. Wall rock mineralized, and vein-filling deposited, before or after the arrival of the gold-bearing solutions would be barren. Veins formed prior to the advent of the gold-bearing solutions may have been re-opened by subsequent fracturing and enriched by the incoming of later auriferous vein matter. On the other hand, many gold-bearing veins were probably re-opened and the fractures filled by barren vein matter, thereby diluting the original vein filling and decreasing the value of the vein as a whole.

In some instances, especially in very wide veins, the bulk of the vein filling was introduced during the late or non-auriferous stage of vein formation, and any gold values are confined largely to the pyrite in the adjoining wall rocks. In such cases the writer believes that the auriferous pyrite was deposited prior to the large-scale introduction of barren vein matter. In other deposits

the wall rocks are unmineralized (by pyrite) and barren, and the gold is confined to the vein matter. In such cases the vein filling is believed to have been introduced toward the close of the gold-depositing stage and at a time when the solutions were no longer capable of producing hydrothermal alteration of the wall rocks.

One also finds that there is a tendency for the gold values to disappear toward the extremities of a vein. As the extremities of a fracture would be the last portions to open up, they would obviously receive solutions that were later in the sequence of mineralization than those which occupied the main part of the fracture. Commonly these solutions were sufficiently late in the sequence to be non-auriferous.

It is a matter of some concern in the Porcupine area that the gold content (in vein matter and wall rock combined) generally falls below commercial grade when the veins pass from greenstone into porphyry. This condition may be due (*a*) to variations in the intensity of mineralization, (*b*) to the chemical inhospitality of the porphyry, or (*c*) to the formation and filling of fractures in porphyry late in the sequence of mineralization.

(*a*) The gold may be present in the vein matter and/or in the pyritized wall rock. The locus of deposition appears to vary with the intensity of mineralization and with the chemical composition of the wall rock. In any one type of rock, the development of pyrite depends on the abundance and potency of the sulphur compounds in the vein-forming emanations. Thus, the intensity of mineralization may be judged by the amount of pyrite per cubic foot of wall rock. There appears to be a fairly consistent relationship between the gold content and the volume of pyrite in the wall rock. The relative proportions of the gold content contained in the vein filling and in the wall rock vary with the intensity of mineralization. Where pyritization has been extensive, the wall rock normally contains a relatively large proportion of the total gold content. Where little or no pyritization of the wall rock has taken place, the gold, if present at all, is almost totally confined to the vein filling.

(*b*) The development of pyrite is dependent upon the presence

of ferrous minerals in the wall rock as well as upon the abundance and potency of the sulphur compounds in the vein-forming emanations. It is apparent, therefore, that the chemical composition of the wall rock, through its control over the formation of pyrite, is an important factor in determining the locus of gold deposition. As the porphyry contains about 1.5 per cent. of ferrous iron, and the greenstones 9 or 10 per cent., it is evident that the former would be far less favorable for the development of pyrite than the latter. In view of the close association of gold with wall-rock pyrite, one would expect the gold content per unit of volume to be much lower in porphyry than in greenstone wall rock. Not infrequently, ore zones (vein matter plus pyritized wall rock) in greenstone become unprofitable on passing into porphyry because the ore widths have been reduced below the limit of economical extraction by the decreased gold content in the walls.

(*c*) The writer believes that most of the low-grade and barren vein matter in porphyry occurs in spaces created and occupied late in the sequence of fracturing and mineralization, when the vein-forming solutions no longer contained much gold. There is no apparent reason why vein matter in porphyry should not be as rich in gold as vein matter of equivalent age deposited in greenstone.

SUMMARY.

In the foregoing paper the writer presents the following conclusions:

The quartz porphyry bodies are believed to be related to the Algoman granitic intrusions. They were affected by shearing and fracturing before vein deposition began. The vein systems are structurally but not genetically related to the porphyry bodies.

The location, size, shape, and other physical characteristics of the quartz veins were determined primarily by structural deformation.

The principal period of vein formation can be divided, on evidence of structural readjustments, into three stages.

The greenstones, due to their relatively high ferromagnesian content, have been more profoundly affected by hydrothermal

alteration than the quartz porphyry. Analyses show that such alteration has involved conspicuous gains in sulphur and potash and a marked loss of silica.

Alteration of the wall rocks cannot be regarded as evidence of vein enlargement by replacement. A study of the chemical and mineralogical changes involved affords convincing evidence that such alteration played no part in the enlargement of the veins.

The presence of so-called relic inclusions of country rock in the vein matter is evidence, not of incomplete replacement of wall rock by vein matter, but of intra-vein shearing and fracturing during the period of vein formation.

Vein enlargement and the presence of "floating" inclusions of country rock in the vein matter can be satisfactorily accounted for by structural deformation repeated at intervals during the period of vein deposition.

Mineralization was a single, continuous process, in which the vein minerals were deposited in a definite sequence.

Gold deposition took place during a relatively long interval in the period of mineralization. It began with the development of auriferous pyrite in the wall rocks adjoining the veins. As the intensity of mineralization diminished, the deposition of gold was more and more restricted to the vein filling. In veins formed late in the sequence of deposition, the gold, if present at all, is confined to the vein matter, the wall rocks being unmineralized and barren.

The presence of ore shoots is directly dependent on the creation and filling of open spaces during the interval of gold deposition. Barren veins deposited prior to the appearance of gold in the vein-forming solutions may have been enriched as the result of subsequent fracturing and the introduction of auriferous vein matter. Conversely, the gold content in some veins was probably diluted by the introduction, toward the close of the period of mineralization, of barren vein matter.

Vein zones (vein matter plus mineralized wall rock) in porphyry are usually lower in grade than those in greenstone. This condition may be ascribed in part to the fact that the porphyry

is chemically less favorable to the development of auriferous pyrite than the greenstones, and in part to the probability that many of the veins in porphyry were formed late in the sequence of mineralization, when the solutions had been largely depleted of their gold content.

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RELATIONS OF CHALCOCITE–STROMEYERITE–ARGENTITE.[1]

G. M. SCHWARTZ.

INTRODUCTION.

STROMEYERITE ($Ag_2S.Cu_2S$) is of special interest in ore deposits because it is composed of the chalcocite and argentite units which form the two most important minerals of copper and silver ores, respectively. In view of the abundance of the constituent units it is somewhat surprising that stromeyerite is comparatively rare, although modern methods of identification have shown that it is more common than formerly supposed. The writer found the mineral reported in the literature as occurring in 27 districts and no doubt this list is not complete. Stromeyerite can usually be recognized in intimately mixed copper-silver ores only by microscopic studies of polished surfaces. Some so-called stromeyerite specimens have proven to be mechanical mixtures of copper and silver minerals. In other silver-bearing copper ores, however, the chemically combined stromeyerite has been recognized as the mineral carrying the silver.

Guild[2] first described the detailed microscopic relations of stromeyerite in copper-silver ores and raised several questions regarding the origin of stromeyerite and the textures which it exhibits. The experimental work which forms the basis of this paper was undertaken in the hope of answering some of these questions.

The writer is indebted to Dr. M. M. Stephens who, as research assistant throughout the work, was responsible for carrying out many of the experiments. Dr. John W. Gruner, by generous assistance, made possible the X-ray work. Dr. W. F. Foshag,

[1] Presented before the Society of Economic Geologists, Chicago meeting, Dec., 1933.

[2] Guild, F. N.: A Microscopic Study of Silver Ores and Their Associated Minerals. ECON. GEOL., vol. 12, pp. 297–353, 1917.

United States National Museum, Professor L. C. Graton, and Dr. C. M. Farnham, kindly furnished specimens for work on jalpaite. Finally, the large amount of detailed experimental work which was necessary in certain phases of the problem would have been impossible without generous grants from the Graduate School of the University of Minnesota.

REVIEW OF LITERATURE.

Stromeyerite has long been recognized as a distinct mineral. It was first analyzed by Stromeyer in 1816,[3] but there was evidently confusion as to its true nature. Some believed it to be a variable isomorphous mixture of the copper and silver molecules, others thought it a definite compound with a 1:1 ratio between the silver and cuprous sulphide. The latter explanation was shown to be correct by Guild [4] and later by Kalb and Bendig.[5] Guild has also described many features of the mineral in later papers.[6] He notes two principal types of occurrences, (1) in veinlets and areas in tetrahedrite, and (2) as a replacement product of bornite, where it plays the same rôle as chalcocite. Other less common occurrences are intergrowths between stromeyerite and galena, also between stromeyerite and argentite. Frequently found was an oleander-leaf texture which was originally thought to be a result of unmixing but later was shown to be due to a transformation or recrystallization induced by heat.

Stromeyerite also occurs as inclusions in chalcocite,[7] and as a pseudo-eutectic intergrowth with tennantite.[8] Whitehead [9] has

[3] Doelter, C.: Handbuch der Mineralchemie, vol. 4, p. 278, 1926.

[4] *Op. cit.*

[5] Kalb, G., and Bendig, M.: Erzmikroskopische Untersuchung der Mineralreihe Silberglanz-Kupferglanz. Centr. für Min., 1924, pp. 516–519.

[6] Guild, F. N.: The Enrichment of Silver Ores. In Fairbanks: The Laboratory Investigation of Ores, pp. 200–239, 1928.

Guild, F. N.: The Micro-structure and Paragenesis of Stromeyerite. Schweiz. Min. Petr. Mitt., vol. 12, pp. 222–233, 1932.

[7] Schwartz, G. M., and Park, C. F.: A Microscopic Study of Ores from the Campbell Mine, Bisbee, Arizona. ECON. GEOL., vol. 27, pp. 39–51, 1932.

[8] Lindgren, W.: Pseudo-eutectic Textures. ECON. GEOL., vol. 25, pp. 1–13, 1930.

[9] Whitehead, W. L.: The Veins of Charniallo, Chile. ECON. GEOL., vol. 14, pp. 1–45, 1919.

described ruby silver replaced during enrichment by argentite, stromeyerite and stephanite. Bastin [10] notes stromeyerite replacing sphalerite, and bournonite also contemporaneous with chalcocite in supergene ores. Graphic or pseudo-eutectic intergrowths have been described by Schwartz and Park [11] and by Burbank.[12]

Ramdohr [13] showed that the bladed or " oleander-leaf " structure described by Guild was due to an inversion when the mineral was heated. Guild [14] has confirmed this conclusion in his latest paper.

EXPERIMENTAL METHODS.

In order to carry on experiments involving chalcocite, argentite and stromeyerite it was found necessary to manufacture stromeyerite because of the scarcity of the natural mineral. This was done by making briquets of chalcocite and argentite which could be polished and then converted to stromeyerite by heat treatment. The Ag_2S used was prepared by Dr. R. B. Ellestad by precipitation with H_2S from a silver chloride solution; the precipitate was washed several times and dried. The chalcocite used in all experiments came from an exceptionally pure lump from Messina, Transvaal, which Dr. F. F. Grout presented to the writer.

Analysis of Chalcocite from Messina, Transvaal, Africa.

Analyst, R. B. Ellestad.

Cu.	S.	Fe.	Total.
79.24	20.00	0.20.....	99.64

The chalcocite was ground in an agate mortar to pass a 100-mesh screen, definite percentages of Ag_2S were added, and mixed by further grinding in the mortar. The mixture was then placed in a steel cylinder and compressed in a hydraulic press at pressures

[10] Bastin, E. S.: Silver Enrichment in the San Juan Mountains, Colorado. U. S. Geol. Survey Bull. 735–D, p. 100, 1922.

[11] Schwartz, G. M., and Park, C. F.: Pseudo-eutectic Textures (Discussion). ECON. GEOL., vol. 25, pp. 658–663, 1930.

[12] Burbank, W. S.: Geology and Ore Deposits of the Bonanza Mining District, Colorado. U. S. Geol. Survey Prof. Paper 169, p. 64, 1932.

[13] Schneiderhohn-Ramdohr: Lehrbuch der Erzmikroskopie, vol. 2, pp. 303–305, 1931.

[14] *Op. cit.*, Min. Petr. Mitt., 1932.

up to 16,000 pounds per square inch.[15] Fragments of the briquets were polished, then sealed in pyrex tubes for heating at a temperature up to 600° C., and in silica tubes for temperatures above that. The tubes were heated in an electric furnace in which the temperature was measured by means of a thermocouple and potentiometer. Some of the sealed specimens were quenched in water, others cooled slowly. Table I consists of a list of experiments with compositions, temperatures, and rates of cooling, and summarizes the most significant data regarding the experiments.

After cooling, each specimen was lightly polished and examined under the microscope with vertical illumination, then with polarized vertical light, after which they were studied at high magnifications on a Leitz metallograph on which they were subjected to light etching according to the methods recently described by Stephens.[16] Following these tests, each specimen was given the usual etch tests with HNO_3, HCl, KCN and $FeCl_3$. Polarized light and light etching tests were more useful than chemical tests in distinguishing between the three minerals, the chemical reactions being too similar to be very certain. KCN is the best reagent to bring out the bladed structure (Fig. 1). On polished surface stromeyerite is easily distinguished from chalcocite and argentite by its high anisotropism, also by its slight purplish color. Finally, X-ray powder diagrams were secured of the more important natural and artificial specimens.

Experimental Data.—The first experiments were made to determine if stromeyerite could be made by heating chalcocite and argentite below the fusing points of any combinations. It was found that stromeyerite can be quickly and easily made by temperatures as low as 75° C., and as shown below, it will form even at room temperature when the two constituent sulphides are compressed. This is believed to be the first described synthesis of stromeyerite, although it may well have formed, but escaped

[15] See Amer. Miner., vol. 17, pp. 478–484, 1933, for details of the process of making briquets of synthetic minerals.

[16] Stephens, M. M.: Effect of Light on Polished Surfaces of Silver Minerals. Amer. Miner., vol. 16, pp. 532–549, 1931.

notice, in other experiments involving copper and silver sulphides. For comparative purposes, natural stromeyerite was examined from the following localities: Gowganda, Ontario; Colquijirca, Peru; Iquiquo, Chile; Silver King mine, Arizona; Mount Sopris, Colorado; Campbell mine, Bisbee, Arizona. X-ray data described below show that the synthetic stromeyerite is identical with the natural mineral.

Following the successful synthesis of stromeyerite, several experiments were made to determine if the bladed structure was a result of unmixing, a possibility suggested by Guild.[17]

That there is unmixing of stromeyerite from a solid solution of Ag_2S and Cu_2S seems to be rather conclusively shown by a series of experiments involving briqueted material of the composition Cu_2S–75 per cent., and Ag_2S–25 per cent. (Table I, nos. 7, 10, 15, 64). This material, when heated at 250° for 72 hours and cooled by shutting off the furnace, showed a small amount of stromeyerite. Part of the specimen was returned and heated at 300° for 90 hours, after which it was quenched in water. The specimen then showed little if any stromeyerite. Part of the returned material, heated to 300° and cooled slowly, shows abundant stromeyerite in chalcocite. It was also observed that the most diagrammatic bladed form of stromeyerite was found in specimens where there was an excess of chalcocite, that is, from 50 to 75 per cent. of the Cu_2S molecule. This also suggests unmixing of the stromeyerite blades. This in no sense invalidates the conclusions of Kalb and Bendig, and Guild, that the bladed or "oleander-leaf" structure forms by inversion. It does form by inversion, as has been conclusively shown by the experiments tabulated below, but it also seems conclusive that similar blades develop during the unmixing of a solid solution of Ag_2S in Cu_2S. Specimens heated at 200° or higher always showed the "oleander-leaf" structure. Natural stromeyerite and that formed at low temperatures did not show the structure but on exposure to the heat of illumination by arc light under the microscope, the structure developed. The temperature of the inversion that causes the structure in pure stromeyerite is discussed below.

[17] Guild, F. N.: *Op. cit.*, ECON. GEOL., vol. 12, p. 312.

TABLE I.

TABULATION OF EXPERIMENTS.

No.	Composition.		Temperature ° C.	Time Hours.	Rate of Cooling.	Product.
	Cu_2S %.	Ag_2S %.				
1	50	50	260	20	Air Quench	S + C
2	50	50	285	72	Quench, reheat, cooled in furnace	S + C
3	50	50	300	48	Quench in water	S + C
4	39.11	60.89	285	72	Cooled in furnace	S
5	39.11	60.89	300	120	" " "	S + silver
6	90	10	300	120	" " "	C
7	75	25	250	96	" " "	C + S
8	20	80	300	96	" " "	A + S
9	90	10	200	120	Slow cool, 5 hours	C
10	75	25	200	120	" " " "	C + S
11	50	50	200	72	Cooled in furnace	S + C
12	50	50	300	72	Slow cool, 7 hours	S + C
	No. 4	returned				
13	50	50	300	48	Quench in water	S + C
14	90	10	300	96	" " "	C
	No. 7	returned				
15	75	25	300	96	" " "	C + S
	No. 14	returned				
16	90	10	300	24	Slow cool, 20 hours	C
17	50	50	165	72	" " 5 "	S + C
18	39.11	60.89	300–	96	Quench in water	S + C + silver
	No. 18	returned				
19	39.11	60.89	300	48	Slow cool, 5 hours	S + silver
20	50	50	110	96	" " 1½ "	S + C
21	65	35	200	72	" " 5 "	S + C
22	65	35	100	72	" " 5½ "	S + C
23	65	35	75	72	Cooled in furnace	S + C
24	39.11	60.89	200	72	Slow cool, 5 hours	S
25	20	80	200	72	" " " "	A + S
26	65	35	200	90	Quench in water	S + C
27	No. 26	returned				
	65	35	200	115	Slow cool, 6½ hours	S + C
28	39.11	60.89	75	72	" " 3 "	S
29	39.11	60.89	500	3	Cooled in furnace	S + silver
30	39.11	60.89	800	4	" " "	S
31	5	95	200	72	Slow cool, 5 hours	A
32	90	10	900	1½	" " 10 "	C
33	75	25	900	1½	" " " "	S + C
34	65	35	800	1½	" " " "	S + C
35	20	80	800	1¼	" " " "	A
36	90	10	1000	3	" " 6 "	C
37	30	70	700	2	" " 7 "	S + ?
38	39.11	60.89	700	2	" " " "	S
39	20	80	700	2	" " " "	A
40	50	50	700	2	" " " "	S + C
41	39.11	60.89	650	3	" " 20 "	S
42	30	70	650	3	" " " "	S + silver
43	20	80	650	3	" " " "	A
44	10	90	650	3	" " " "	A
45	39.11	60.89	675	2	Cooled in furnace	S
46	30	70	675	2	" " "	S
47	20	80	675	2	" " "	A
48	10	90	675	2	" " "	A
49	10	90	725	1	Slow cool, 6 hours	A
50	15	85	680	72	" " " "	A + S
51	15	85	700	2	" " " "	A + S
52	75	25	700	1	Cooled in furnace	A + S
53	95	5	250	24	" " "	C
54	10	90	300	24	" " "	A
55	15	85	300	24	" " "	A + S?
56	85	15	270	48	" " "	C
57	50	50	100	72	Cooled with boiling water	S + C
58	50	50	90	72	Cooled in furnace	S + C
59	50	50	95	4	" " "	S + C
60	50	50	750	24	" " "	— —
61	65	35	775	24	" " "	— —
62	30	70	250	48	" " "	S + A
63	17.6	82.4	300	72	" " "	A
64	75	25	300	1	" " "	C + S
	No. 15	returned				
65	85	15	300	48	" " "	C

Abbreviations used: A = Argentite, C = Chalcocite, S = Stromeyerite.

Note: The furnace cooled from 275° to 75° in four hours when the current was turned off. When slow-cooled, the current was gradually reduced, thus decreasing the rate of cooling.

Several experiments were made to determine to what extent Cu_2S and Ag_2S are soluble in each other. All the evidence at hand indicates a considerable solubility at both ends of the system Ag_2S–Cu_2S. At least 15 per cent. Ag_2S seems to dissolve in Cu_2S without developing new phases that we have been able to distinguish either by microscopic or X-ray studies. Table I shows the experiments made with 5, 10 and 15 per cent. respectively of Ag_2S. A briquet in which 25 per cent. of Ag_2S was used, developed abundant stromeyerite, with chalcocite clearly left in excess. Other experiments with 35 and 50 per cent. of Ag_2S also showed abundant stromeyerite with excess chalcocite.

At the silver sulphide end of the series the situation is complicated by the supposed existence of jalpaite ($Cu_2S.3Ag_2S$) as a definite compound. The experiments tabulated above show no phase definitely separable from argentite for specimens with 95, 90, 85, 82.4 and 80 per cent. of Ag_2S except that a few with 80 and 85 per cent. showed minor amounts of stromeyerite. Even in these samples it may be suspected that uniformity was not reached in the diffusion by which the solid solutions were formed. With a composition of 70 per cent. Ag_2S, abundant stromeyerite forms with a small excess of argentite.

Stromeyerite is the only mineral formed when the theoretical proportions of Ag_2S (60.89) and Cu_2S (39.11) are used.

FIG. 1. Synthetic stromeyerite etched with KCN; bladed structure. Exp. 20. × 240.

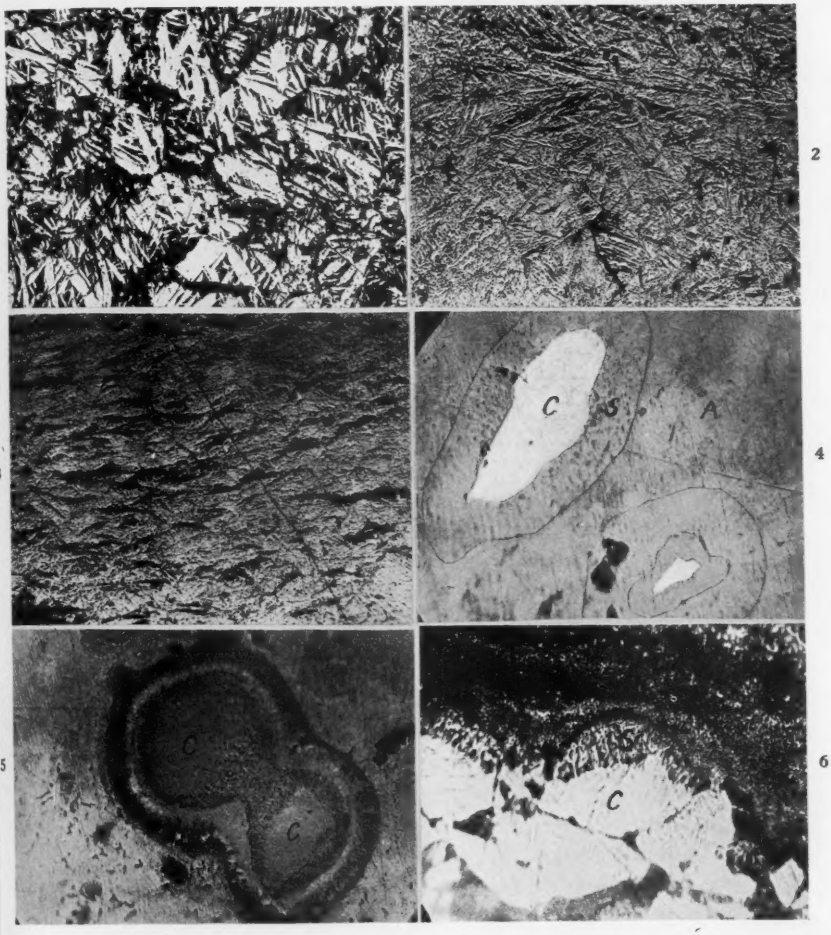
FIG. 2. Bladed structure developed in synthetic stromeyerite by light etching. Exp. 20. × 120.

FIG. 3. Polished surface of stromeyerite, Silver King mine, Arizona; after heating to 107° in microfurnace. × 68.

FIG. 4. Chalcocite (C) grain embedded in Ag_2S (A) and compressed under 16,000 pounds pressure. Zone around chalcocite is stromeyerite (S). × 160. (Retouched.)

FIG. 5. Same specimen as Fig. 4, but light etched to emphasize rim of stromeyerite around chalcocite (C). × 160.

FIG. 6. Contact of chalcocite (white) and Ag_2S darkened by light etching. Part of chalcocite grain (C) was altered to stromeyerite (S) at normal temperature under pressure of 16,000 pounds per square inch. × 160.



FIGS. 1–6

INVERSION OF STROMEYERITE.

Ramdohr [18] noted that only those specimens which had been subjected to heat by impregnation in sealing wax showed the "oleander-leaf" structure, and correctly inferred that this was due to an inversion in crystal structure, which he believed to be from orthorhombic to isometric. The melting point of the sealing wax used in the experiments described in this paper is 128° C. Thus the inversion temperature was known to be below this point.

The principal difficulty in attempting to determine the inversion point accurately is in obtaining even small amounts of pure natural stromeyerite. Several methods were tried where small amounts of material would suffice. Dr. M. M. Stephens designed and built a small electric furnace which could be mounted on the stage of a Leitz metallograph. Thus the polished surface could be observed while the temperature was gradually raised. A polished specimen of stromeyerite from the Silver King mine, Arizona, was used. The first change was recognized at 97° C. and at about 100° C. the bladed structure was clearly developed (Fig. 3). The process seemed complete at 107° C.

It was realized that the temperature obtained by the micro-furnace was probably somewhat high, due to the difficulty of maintaining a constant temperature for very long.

In the next experiments a series of specimens of synthetic stromeyerite which had been prepared by heating at 70° C. for 72 hours were sealed in pyrex tubes in the usual manner and held at constant temperature for varying lengths of time and then examined for bladed structure. The temperatures at which the specimens were held were 90°, 95°, 100°, and 110° C. At 90° no blades were recognized, they were definitely recognizable at 95° and 100°, and at 110° they were well developed. The change was so slight when held at 95° for four hours that it was concluded that the inversion temperature was very close to that figure.

As a further check and more accurate determination, the re-

[18] Schneiderhöhn-Ramdohr: *Op. cit.*

maining portion of a briquet of chalcocite and precipitated Ag_2S in the theoretical proportions of stromeyerite was heated at 250° C. for 72 hours and cooled in the furnace, after which the anisotropism indicated it to be entirely converted to stromeyerite. This was then finely ground in an agate mortar and the entire amount, about five grams, was packed in a glass tube with a cromel-alumel

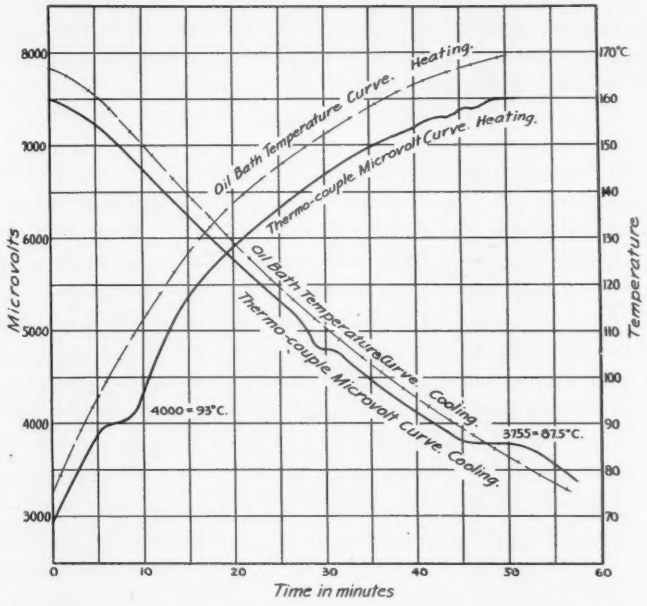


FIG. 7. Curves showing inversion points of stromeyerite on heating and cooling.

thermocouple. The tube was mounted in an oil bath on a hot plate with a mercury thermometer for measuring the bath temperature. The E.M.F. was read on a Leeds and Northrup potentiometer at intervals of one minute, and the bath temperature was read at the same intervals on a mercury thermometer. Four heating and three cooling curves were run (Fig. 7). The thermo-

couple standardization was rechecked against ice and boiling water. The inversion point of stromeyerite is clearly indicated by a break in each heating curve at about 4000 microvolts, which is equivalent to 93°. On the cooling curve the inversion is somewhat lower, about 88°. The lower inversion on cooling is to be expected, as shown by Posnjak, Allen and Merwin.[19]

It thus seems established that the inversion point of stromeyerite is very close to 93°. Some allowance should be made for experimental errors of work done without highly specialized equipment, as has been shown by the variable inversion and melting points obtained for the same substance by different investigators.

The fact that the inversion point as determined above is very close to that of chalcocite (91°) raises the question as to the possibility of the observed reaction being due to uncombined portions of that mineral. The fact that only five grams of material was used and this uniformly showed the high anisotropism of stromeyerite on polished surface before being powdered, seems to preclude the possibility of there being enough chalcocite present to give a recognizable effect. It should be noted that this stromeyerite was formed by heating well above the temperature used in determining the inversion.

JALPAITE.

Mixtures of the approximate composition attributed to jalpaite (Ag_2S = 83.37 per cent.; Cu_2S = 17.63 per cent.) were heated at various temperatures (Table I). One sample was prepared of exactly this composition, compressed and heated at 300° for three days. None of these specimens revealed a compound or mineral species distinct from argentite and stromeyerite. Most specimens seemed to be essentially argentite, some showed small amounts of stromeyerite. This seemed to throw doubt on jalpaite as a distinct mineral species, and considerable time was spent in investigating this question.

[19] Posnjak, Allen and Merwin: The Sulphides of Copper: ECON. GEOL., vol. 10, pp. 491–535, 1915.

Jalpaite was described and named by Breithaupt [20] on the basis of material from Jalpa, Mexico. An analysis by T. Richter (Table II) showed this material to closely approximate the composition indicated by the formula $3Ag_2S.Cu_2S$. Later, Bertrand [21] analyzed material from Tres Puntas, Chile, which also proved to be close to $3Ag_2S.Cu_2S$.

A review of much of the data on the mineral up to 1924 is given by Doelter.[22] Descriptions mainly referring to polished surfaces have been published by Murdoch,[23] Davy and Farnham,[24] Kalb and Bendig,[25] Farnham,[26] and Schneiderhöhn and Ramdohr.[27]

The writer was informed by Professor Graton [28] that the specimens used by Murdoch were later shown to be pearcite and stephanite, thus eliminating this description. According to a communication from Dr. Farnham, it was probably the same material used for the tables prepared by him. The material from Tres Puntas, Chile, described in both 1920 and 1931 as having a blood-red internal reflection, is probably related to the ruby silvers rather than to argentite, stromeyerite and chalcocite, which show no evidence of a red internal color. Schneiderhöhn and Ramdohr state that the mineralogical identity of the specimen used by them was not established beyond doubt. This seems to throw doubt on all mineralographic descriptions except that by Kalb and Bendig. They investigated jalpaite from Smeinogorsk, in the Altai Mountains. It corresponds closely in most respects to argentite except that it is anisotropic. Their analysis, except sulphur, corresponds closely with the theoretical composition.

[20] Breithaupt, C.: Berg- und Hüttenmännische Zeitung, vol. 17, p. 85, 1858.

[21] Bertrand, P.: Annales des Mines, vol. 1, p. 413, 1872.

[22] Doelter, C.: *Op. cit.*, pp. 275–277.

[23] Murdoch, J.: Microscopical Determination of the Ore Minerals, p. 140. New York, 1910.

[24] Davy and Farnham: Microscopic Examination of the Ore Minerals, p. 67. New York, 1920.

[25] Kalb and Bendig: *Op. cit.*, pp. 516–519.

[26] Farnham: Determination of the Opaque Minerals, p. 29. New York, 1931.

[27] Schneiderhöhn-Ramdohr: *Op. cit.*, pp. 306–307.

[28] Personal communication.

TABLE II.

ANALYSES OF JALPAITE.

	1.	2.	3.	Theoretical.
Cu	13.12	13.06	14.10	14.06
Ag	71.51	71.63	71.73	71.73
S	14.36	14.02	16.33	14.21
Fe	0.79	0.57	——	——
	99.78	99.28	102.16	100.00

1. Breithaupt, A.; Berg- und Hütt. Zeitung, vol. 17, p. 85, 1858.
2. Bertrand, P.: Annales des Mines, vol. 1, p. 413, 1872.
3. Kalb and Bendig: Centr. für Miner., 1924, p. 517.

As noted above, none of the writer's experiments indicated the existence of a distinct compound of the composition of jalpaite. This contrasts strikingly with synthetic stromeyerite, which was easily obtained and recognized beyond doubt. Checking both natural and synthetic material by means of X-ray powder diagrams also fails to show a separate pattern for jalpaite. The natural material tested was a small fragment of one of two crystals in the United States National Museum collection which came from Hostotipaquillo, Mexico. There was barely enough of this material for an X-ray diagram and a small polished surface. The polished surface showed that the crystal was replaced around the outside by a narrow rim of covellite. Chemical etch tests and light etching gave reactions like those of argentite. The powder diagram also showed the argentite pattern. Unfortunately, not enough material is available for analysis, but if the mineral contains copper other than that in the covellite it is in solid solution in the argentite.

All of the writer's work tends to throw doubt on the existence of jalpaite as a distinct mineral. The earlier descriptions can not be relied on because they were not based on microscopic examination of polished surfaces, and admixed covellite or chalcocite would easily escape detection, as was shown by the covellite in the specimen from the United States National Museum. The present work would suggest that many so-called jalpaites are solid solutions of Cu_2S and Ag_2S. The chief evidence that some jal-

paites are a definite compound seems to be the rather remarkable correlation between the three available analyses (Table II) and the theoretical composition. Kalb and Bendig note the anisotropism as a means of distinguishing from argentite, but argentite shows anomalous anistropism in some specimens. If all jalpaites are solid solutions a wider range in composition would be expected. Pending further work on natural material, jalpaite may be considered a doubtful species.

X–RAY DATA.

X-ray powder diagrams were made of several of the natural and synthetic minerals and mixtures used in the experiments. These served as checks on the microscopic determinations and several are plotted on Fig. 8 for ease of comparison; others not plotted were used in arriving at the conclusions stated in this paper. In practically all cases there was a close correspondence between the microscopic diagnosis and the mineral species as inferred from the X-ray data. Conclusions which were confirmed by the patterns are as follows:

1. The synthetic argentite briquets made from Ag_2S precipitated from solution with H_2S have a crystal structure identical with that of argentite crystals from Sardinia. (See Figure 8.)

2. Stromeyerite made by heating a briquet of Ag_2S–61.89 per cent. and Cu_2S–39.11 per cent. for 66 hours at 200° C. is identical with natural stromeyerite from Gowganda, Ontario. Exper. 28, Table I.

3. Precipitated Ag_2S briqueted with 10 per cent. of natural chalcocite and heated for 120 hours at 200° shows a pattern identical with the natural argentite, except for two faint lines. Exper. 44, Table I.

4. Natural chalcocite briqueted with 10 per cent. of precipitated Ag_2S and heated for 3 days at 200° shows a pattern much like that of the pure chalcocite. Exper. 9, Table I.

5. Patterns of so-called jalpaite from Mexico, and of a briqueted mixture of Ag_2S—82.4 and chalcocite—17.6 heated for 3 days at 300° C. are very much like that of pure argentite. No

essentially different space lattice for jalpaite is indicated. (See Fig. 8.)

6. The pattern of the composition Ag_2S–70 per cent. and Cu_2S–30 per cent. briqueted and heated for 48 hours at 250° is practically like that of stromeyerite, but where its lines coincide

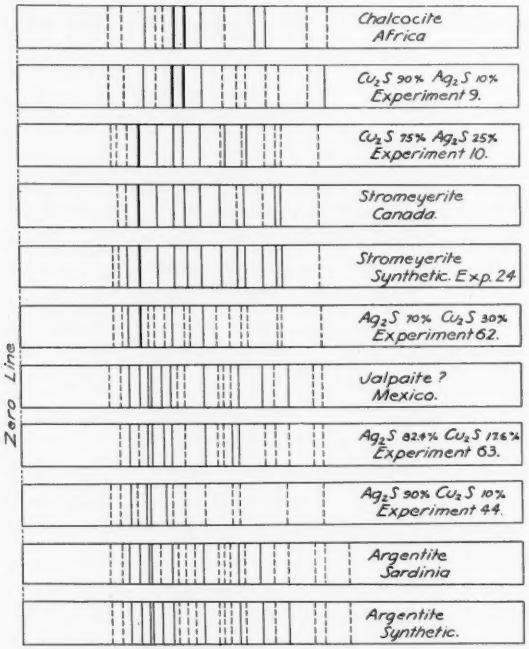


FIG. 8. X-ray powder diagrams of stromeyerite, argentite, chalcocite and mixtures.

with those of argentite they seem slightly more intense. Both stromeyerite and argentite are judged to be present.

7. Patterns for compositions of 50 and 75 per cent. Cu_2S show essentially the stromeyerite pattern although subordinate amounts of chalcocite may be seen microscopically.

DIFFUSION UNDER PRESSURE.

Polished surfaces of several briquets composed of finely ground natural chalcocite and chemically precipitated Ag_2S which had been subjected to pressures up to 16,000 pounds per square inch for several hours, show that a narrow rim (Fig. 4) around the chalcocite fragments was slightly darker (a purple tinge) than either chalcocite or argentite and that this rim reacted differently than either of these minerals to chemical tests and to light etching (Fig. 5). Every possible method of determination was applied to this material, and all showed that it was stromeyerite. Several special experiments were then made compressing the two materials, and all showed conclusively that stromeyerite is developed at room temperature when Cu_2S and Ag_2S are subject to high compression. Fig. 6, for example, shows the contact between chalcocite and argentite on the edge of a briquet where the chalcocite was placed on the bottom of the cylinder and the precipitated Ag_2S on top, thus giving a sharp line of demarcation. After compression, when etched with $FeCl_3$, a narrow iridescent band of stromeyerite may be seen even with the naked eye. The high anisotropism also distinguishes this mineral. After light etching it is clear that nearly one half of the fragment of chalcocite marked C has been converted to stromeyerite.

In some briquets of ground chalcocite and Ag_2S it was noted that each fragment of chalcocite was surrounded by a zone of stromeyerite formed by diffusion at the contact. Stromeyerite is slightly purplish on a highly polished surface as compared with argentite and chalcocite. It was also observed that if the contact between the two minerals was not perfect, stromeyerite was not formed. When well polished and examined at magnifications of 200 diameters or higher, it was noted that stromeyerite not only forms in the zone around the chalcocite, but also develops along the parting [29] of the chalcocite, forming a serrate edge or blades penetrating into the fragment. No doubt the stress to which the chalcocite is subjected on compression aids the development of stromeyerite by a tendency to shearing along the cleavage planes of the chalcocite.

[29] Parting is well shown in the specimen from Messina, Africa, used in these experiments.

Examination of the zones of stromeyerite in polarized light shows that commonly the elongation of the bladed crystals in the zones is oriented normal to the contact of chalcocite and argentite.

In specimens containing a great excess of Ag_2S, for example Ag_2S–85 per cent., Cu_2S–15 per cent., the stromeyerite formed by diffusion under pressure and then disappeared, due to further diffusion, when the specimen was heated for some time (Exper. 50). Specimens of chalcocite ore containing stromeyerite from the Campbell mine, Bisbee, Arizona, were also heated and the stromeyerite dissolved in the chalcocite. Slow cooling does not seem to result in reprecipitation of stromeyerite. From this, one may suspect that the chalcocite and stromeyerite formed at a relatively low temperature, although the chalcocite is thought to be hypogene.[30]

MELTING POINTS.

In attempting to synthesize jalpaite, it was found advisable to heat some of the mixtures of Cu_2S and Ag_2S to the melting point in order to be more certain that equilibrium would be reached. In this way some data were obtained on the melting points of the mixtures. The melting point of chalcocite is given as 1130° and that of argentite as 825°.[31] The melting points of various compressed mixtures of Cu_2S and Ag_2S are shown on Fig. 9. It is surprising that the stromeyerite, which is a definite compound, shows about the same low melting point as other mixtures near the middle of the diagram. There is also no break in the region of the composition of jalpaite. More complete data are needed on the freezing and melting points of the system Cu_2S–Ag_2S, but the securing of this information depends in a large measure on a satisfactory method of producing pure Cu_2S in considerable amounts or in finding such amounts of practically pure natural Cu_2S. It would be of interest to see how the melting and freezing point diagrams would look in the

[30] Schwartz, G. M., and Park, C. F.: *Op. cit.*, Econ. Geol., vol. 27, p. 51.

[31] International Critical Tables, vol. 1, pp. 122 and 124.

region of the composition of the natural mineral stromeyerite and the less well defined jalpaite.

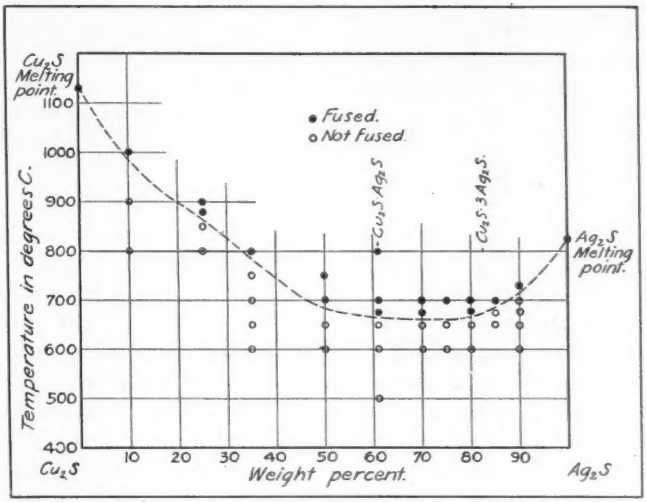


FIG. 9. Diagram showing melting point determinations of various proportions of Ag_2S and Cu_2S.

WIRE SILVER.

In a few experiments involving argentite and mixtures, small amounts of wire silver were formed. Just why this developed is not certain, but it is strongly suspected that small amounts of moisture left from polishing the specimen are responsible. It has been shown by previous investigators that superheated steam causes the formation of native silver.[32] The points that were especially interesting regarding the wires were their relatively great length and their exact resemblance to many natural wires of silver. It seems characteristic for the wires to have a grooved or slickensided appearance on the sides. In the specimens observed

[32] For recent summary see: Douglas, C. B. E.: Native Wire Silver. Inst. Min. and Met. Bull. 341, Feb., 1933. Discussion, *Idem*, Bull. 342, pp. 21–24, 1933. Bischof is there credited with having shown in 1843 the decomposition of argentite to silver by steam.

in the experiments reported above it seemed clear that the slickensiding was due to the silver squeezing out of a small crack or hole in the argentite. The specimens were studied under a binocular microscope and several of the writer's co-workers observed them. All were struck by the same impression that the silver squeezed out of the holes. The suggestion made by Douglas that native wire silver is not necessarily a result of deposition from solution but results from the reduction of argentite seems proved.

CONCLUSIONS.

1. Stromeyerite can be easily synthesized by briqueting powdered Ag_2S and Cu_2S under compression and then heating in sealed tubes at temperatures from 75° C. to the melting point of the mixture.

2. The synthetic stromeyerite produced in the experiments described in this paper has all the usual properties of natural stromeyerite, of which the high anisotropism is most conspicuous.

3. The synthetic stromeyerite when made at a temperature above 100° shows the bladed or "oleander-leaf" structure originally described by Guild.

4. The bladed structure is due to an inversion in crystal structure at 93° C., as shown by heating the mineral on the stage of the microscope and by heating and cooling curves.

5. When Ag_2S and chalcocite are compressed at high pressures, stromeyerite forms in rims along the contact of the two substances by diffusion.

6. There is considerable solubility of Ag_2S in Cu_2S and of Cu_2S in Ag_2S. There may be some solubility of Ag_2S and Cu_2S in stromeyerite, but this is not large. The general limits seem to be about 20 per cent. Cu_2S soluble in Ag_2S, and 15 per cent. Ag_2S soluble in Cu_2S.

7. Jalpaite ($3Ag_2S.Cu_2S$) was not formed as a distinct compound, but specimens of the proper composition proved to be a solid solution of Cu_2S and Ag_2S, which retained the crystal structure of argentite, as shown by X-ray powder diagrams.

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GEOLOGY OF THE ALCOVA DAM AND RESERVOIR SITES, NORTH PLATTE RIVER, NATRONA COUNTY, WYOMING.[1]

WILMOT H. BRADLEY.

INTRODUCTION.

At present the local irrigation development in the vicinity of Casper, Wyoming, is inadequate to supply the stockmen with winter feed and to furnish the city of Casper and nearby oil fields with the necessary foodstuffs. Consequently the construction of a diversion dam high enough to irrigate the large tracts of tillable land along the North Platte River in the vicinity of Casper has long been desired by the community. At Alcova, about 30 miles southwest of Casper, the North Platte flows through a deep and narrow canyon about half a mile long. A dam 175 feet high in this canyon would permit the irrigation of about 66,000 acres of land between Alcova and Casper and so fulfill the community's need.

Alcova Canyon is apparently ideal for the construction of a dam but in reality the geology is such that, in the writer's opinion, only one place in the canyon is suitable for a dam site. It is partly because the geology has played so critical a part in determining the exact position of the dam foundations, and partly because this dam is now about to be built as a part of the Public Works program, that this paper is now published.

In 1921 Homer J. Gault of the Bureau of Reclamation, in co-operation with the State Engineer of Wyoming, made a preliminary survey of the Casper-Alcova irrigation project. The bore holes drilled at that time were inconclusive and no geologic examination was made. In the spring of 1929 the Bureau of

[1] Published with the permission of the Director, U. S. Geological Survey, and the Commissioner, U. S. Bureau of Reclamation.

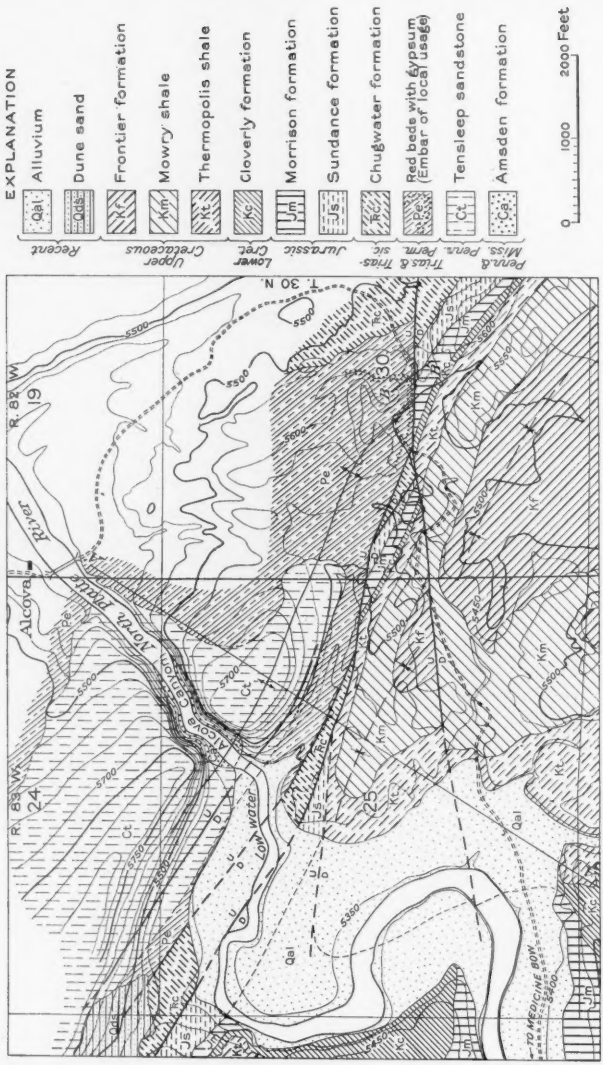

FIG. 1. Geologic map of a portion of the Alcova dam and reservoir sites.

Reclamation requested the Geological Survey to make a geologic examination of the Alcova dam and reservoir sites to see if it was feasible to build a dam there and if so, to select a site. The writer was charged with making that examination, and after a preliminary inspection of the canyon and the reservoir site with Mr. J. R. Iakish, engineer for the Reclamation Bureau, spent 5 days in making a geologic study of the canyon and a portion of the reservoir site. At the time of the writer's visit, engineers of the United States Army Engineer Corps were engaged in making detailed topographic surveys of the canyon and the reservoir site. This work was carried on under the immediate supervision of the Area Engineer, Mr. C. T. Barker, whose willing co-operation greatly facilitated the geologic mapping. The topography shown on the accompanying maps was compiled from photographic copies of the Army Engineers' field sheets.

In the report transmitted to the Bureau of Reclamation in the autumn of 1929 the writer selected a dam site, recommended further exploratory drilling, and suggested that if the dam were built, some sort of broad base dam should be considered. After drilling more holes at the site selected, and others both up and down stream from it, the site selected by the writer was approved and an earth and rock-fill dam with concrete core wall is now about to be constructed. This dam will raise the water approximately 169 feet above the low-water stages of the river.

TOPOGRAPHY.

From the granite gorge in which the Pathfinder dam was built, the North Platte River flows northeastward through a narrow canyon (referred to in this report as the upper canyon) in hard stratified rocks and then out into a broader valley that has a series of rather high, transverse ridges or hogbacks. At the northeast end of this broader valley the river enters a short, steep-walled canyon where the Alcova diversion dam is to be built. The water impounded by this dam will flood a large part of the broader valley and back up a considerable distance into the upper canyon.

FIG. 1. Geologic map of a portion of the Alcova dam and reservoir sites.

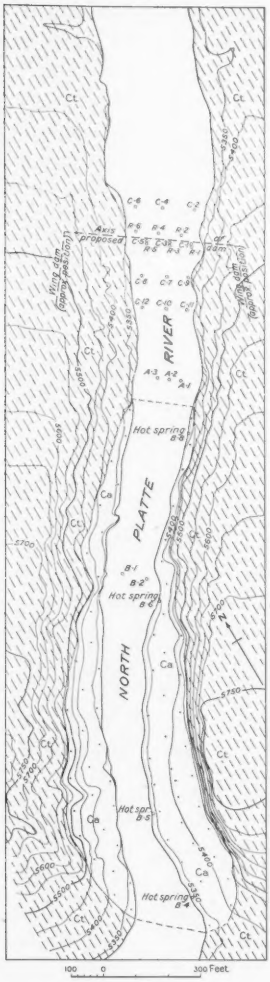

FIG. 2. Geologic map of Alcova Canyon showing the dam site and location of bore holes and hot springs. *Ca*, Amsden formation; *Ct*, Tensleep sandstone. Geology by W. H. Bradley, U. S. Geological Survey. Topography by D. H. McCoskey, U. S. Army Engineer Corps.

TABLE I.

GEOLOGIC FORMATIONS EXPOSED IN THE VICINITY OF THE PROPOSED ALCOVA DAM SITE.

Name.	General Character of the Rocks.	Approximate Thickness in Feet.
Amsden formation (Mississippian and Pennsylvanian)	Limestone beds with few thick beds of limy sandstone; limestone, buff or light gray, not magnesian, rather soft and porous; sandstone fine-grained, light gray, soft	244
Tensleep sandstone (Pennsylvanian)	Sandstone, light gray to buff, fine-grained, soft, poorly consolidated; most beds have a limy cement; units thick and crossbedded on a large scale	235
Embar formation of commercial usage (Permian and Triassic)	Red shaly sandstone with thick beds of gypsum and a few thin beds of limestone	230
Chugwater formation (Triassic)	Predominantly red sandy shale and sandstone; about 350 feet from the top is the Alcova limestone member, which is about 8 feet thick	1,175
Sundance formation (Jurassic)	Lower part, white, pink, and red sandstone; middle part, red muddy sandstone and gypsum beds; upper part, gray silty shale	340
Morrison formation (Jurassic)	Alternating beds of sandstone and soft variegated mudstone	180
Cloverly formation (Lower Cretaceous)	Predominantly sandstone but with few beds of variegated mudstone; bed at base conglomeratic	190
Thermopolis shale (Upper Cretaceous)	Almost black shale	300
Mowry shale (Upper Cretaceous)	Hard blocky or flaky silver-gray shale with soft white bentonite beds	250
Frontier formation (Upper Cretaceous)	Soft, almost black shale; only lower part exposed	900
Dune sand (Recent)	White sand of wind-blown origin; consists of medium-sized, well rounded grains of quartz	1–50
Alluvium and river silt (Recent)	Silt, sand, and gravel in the bed of the present North Platte River, in the narrow flood plains about at flood level of the river, and along the courses of the small side streams	1–30 +

TABLE II.

No. of Bed.	Character of Rock.	Thickness Ft.
	Tensleep sandstone:	
1	Sandstone, yellowish brown, fine-grained, and excessively cross-bedded and jointed; moderately soft with few hard quartzitic layers; soft and limy at top	58
2	Sandstone, brownish, slabby, cross-bedded; soft, fine-grained, sugary texture; without much limy cement except at top	55
3	Sandstone, light gray, fine-grained, soft and with easily soluble limy cement throughout; massive but cross-bedded on grand scale	56
4	Sandstone, light gray, fine-grained, very soft, poorly consolidated but without limy cement	8
5	Sandstone, light gray, fine-grained, soft and with rather easily soluble limy cement; massive but cross-bedded on grand scale	46
6	Sandstone, white, fine-grained, rather soft, with sugary texture; crudely cross-bedded	13
	Amsden formation:	
8	Limestone, light brownish yellow, rather soft, sandy near the base; characterized by numerous round pits in upper surface and numerous closely spaced vertical joints; crushing strength approximately 20,100 lbs. per sq. in.	14
9	Limestone, white to buff, fine-textured, sandy and hard; massive but locally contains large solution caves; hot spring B-8 emerges from a joint near top of bed at river level; crushing strength approximately 13,600 lbs. per sq. in.	20
10	Sandstone, light gray, fine-grained; massive or vaguely cross-bedded; locally hard and quartzitic but generally poorly cemented; crushing strength approximately 10,800 lbs. per sq. in.	5½
11	Limestone, buff, hard, massive and fine-textured, though somewhat porous and cellular as a result of solution; crushing strength probably about same as bed 9	5
12	Sandstone, fine-grained, very soft and limy, gently cross bedded; weak and readily soluble	13
13	Sandstone, pale buff, fine-grained, very soft and friable, with weak limy cement; massive, with rounded surfaces and open, deeply weathered joints	9
14	Limestone, brownish buff, hard and fine-textured though somewhat porous and readily soluble; locally large solution caves; surface weathers hackly	19½
15	Limestone, very sandy, almost a sandstone, light gray, fine-grained, sugary textured, very soft and friable with weak limy cement; lower part cavernous at river level	11
16	Limestone, light buff, crystalline with a rather coarse uneven texture; readily soluble; surface hackly; locally with rather large solution cavities that were former sites of hot springs	26

TABLE II—*Continued.*

No. of Bed.	Character of Rock.	Thickness Ft.
17	Limestone, pinkish lavender, very shaly; thin regular bedding	11
18	Limestone, reddish, hard, sandy, massive	11
19	Limestone, gray, rather massive, hard but readily soluble; at river level has many large solution cavities	43+
	Note: No. 19 is lowest or oldest bed exposed in the section in vicinity of Alcova dam site.	
	Total thickness of rocks exposed in canyon walls	424

ROCK FORMATIONS.

General Statement.—The geologic column in the immediate vicinity of the Alcova dam site is shown in Table I. (See also Figs. 1 and 2.) The limestone beds known as the Amsden formation make up a part of the walls of the Alcova Canyon. This is followed by successively younger formations and ends with the Recent river silt and alluvium.

Certain groups of these beds have a direct bearing on the location of dam, reservoir, or spillway sites and will be described in greater detail.

Details of the Amsden Formation and Tensleep Sandstone.—Together, these two formations make up the anticlinal ridge through which the North Platte River has cut the canyon at Alcova. Because it will be necessary to refer in this report to various beds or groups of beds in the canyon walls, the complete detailed section is given. Bed Number 1 lies like a blanket over the ridge through which Alcova Canyon is cut. It forms the crest, flanks the north slope, and bends down sharply so as to form the greater part of the south slope.

The Embar formation (of local usage), which overlies the youngest or No. 1 bed described above, consists of deep red sandstone and shale interbedded with gypsum and a little limestone. The Gypsum beds are up to 17 feet thick, but most of them are 1 to 4 feet thick. This formation, as here mapped, is about 230 feet thick. It outcrops along the north and south

flanks and around the east end of the Alcova Canyon ridge. Its significance with respect to the water-tightness of the reservoir is discussed further on.

STRUCTURE.

In general, the rocks in the vicinity of the dam and reservoir sites are tilted so that they dip northeastward or eastward at angles of 9° to 13° except where they have been dislocated by faults. The most significant structural feature is a group of nearly parallel large normal faults that trend roughly N. 70° W. and extend along the foot of the south flank of the Alcova Canyon

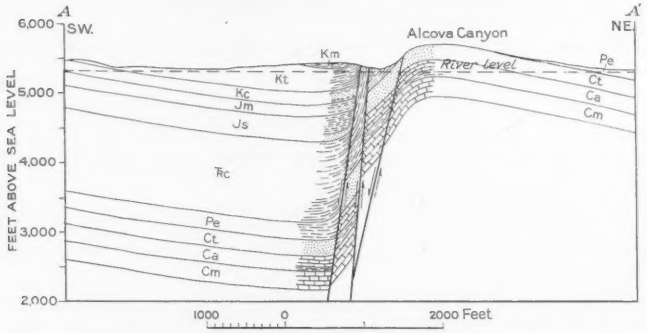

FIG. 3. Diagram showing the interpretation of the geologic structure through Alcova Canyon ridge and a part of the reservoir basin along the line *A–A'* shown on the geologic map, Fig. 1.

ridge. Three of the largest of these faults were recognized in the field and mapped. The rocks south of this fault zone have been dropped approximately 2,400 feet. The relations between the rocks on the two sides of the fault zone are shown diagrammatically in Fig. 3. Between these faults the beds are greatly squeezed, crushed, and distorted. Even some of the relatively hard limestone beds in the Amsden and Tensleep formations have been badly crushed and pinched. Thus, by reason of the drag along these faults the Alcova Canyon ridge is in reality an anticline whose north limb has the regional northeastward inclination

of about 11° and whose south limb consists of the same beds bent down steeply in the opposite direction along the faults. The Alcova Canyon ridge has its present topographic relief because the softer rocks that normally lie adjacent to it on the north, and those that have come to lie adjacent to it on the south by faulting, have been eroded more than the rocks making up the anticlinal ridge.

A little less than one mile east of Alcova Canyon the main fault is offset by a younger fault of considerable size that trends roughly

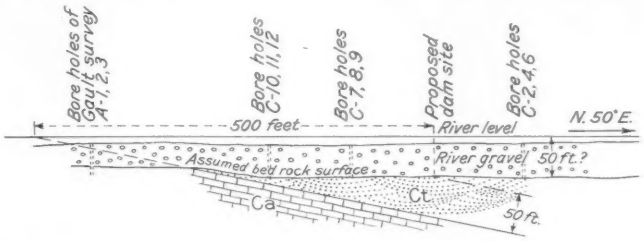

FIG. 4. Diagram showing the attitude and position of the rocks below the river level at the proposed dam site. *Ct*, Tensleep sandstone; *Ca*, Amsden formation.

N. 75° E. and drops the rocks on its south side with respect to those on the north. The trace of this fault coincides with the little saddle through which passes the road from Alcova to Medicine Bow. On the west side of the road in the saddle just mentioned several rather thick beds of gypsum in the Embar formation have been dragged down along the fault so that they are now steeply inclined and strike roughly parallel to the fault (Fig. 5).

HOT SPRINGS.

Yield, Temperature, and Quality of Water.—Four hot springs emerge from the rocks or from the talus slopes a few feet above the low-water level of the river in the east wall of the Alcova Canyon. For reference they are numbered B–4, B–5, B–6, and B–8, and their positions are accurately shown in Fig. 2. At the

time of the writer's visit, the outlet to B–4 was just below the river level so its flow could not be estimated. Spring B–5 was little more than a trickle when first visited, but a few days after the river had risen nearly to the spring, its flow increased considerably and the temperature of the water rose perceptibly. This observation is significant because it indicates a direct and immediate connection between the river level and the flow of these springs. Most of the water from spring B–6 emerges through a 4-inch iron pipe which it fills completely. A sample of the water from this spring was taken for analysis and its temperature then was 129° F. The analysis made in the laboratories of the U. S. Geological Survey is given below.

ANALYSIS OF WATER FROM SPRING B-6 IN ALCOVA CANYON.
(Margaret D. Foster, analyst.)

	Parts per Million.
SiO_2	41.0
Fe	0.1
Ca	157.0
Mg	27.0
Na	199.0
K	14.0
CO_3	0.0
HCO_3	91.0*
SO_4	458.0
Cl	287.0
NO_3	0.05
	1228.0

* Bicarbonate. Converted to carbonate = 45.0.

This spring emerges from a crevice near the top of the thick limestone bed (No. 16, Table II). Spring B–8 has a flow about equal to that of B–6 and emerges from a fissure at the top of the No. 9 limestone bed. Its temperature was not measured.

Source and Probable Head of the Springs.—During the earth movements that tilted and faulted the rocks of this locality, the relatively hard and brittle rocks such as those of the Amsden formation in the core of the Alcova Canyon ridge, were strained, fractured, and opened up along joint and bedding planes. Such channels permitted water to flow through and along these beds. The stratigraphy and structure here are particularly favorable to artesian flow, as shown in Fig. 3. The beds of the Amsden

formation form an asymmetric U-shaped aquifer. Water enters these beds where the river crosses them in the upper canyon, flows through the U-tube and emerges in Alcova Canyon, where the river again cuts across these beds. The hydrostatic head at these springs in Alcova Canyon is roughly equal to the difference in elevation between them and the river surface at the intake in the upper canyon, or about 22 feet.[2] The subsurface water movement from the upper canyon to Alcova Canyon is essentially restricted to the Amsden formation by the overlying fine-grained and cross-bedded Tensleep sandstone and the red shale of the Embar (of local usage) and Chugwater formations, which are all relatively impervious and prevent upward leakage from the aquifer where the head is greatest.

Additional strength is given to the theory that most of the water emerging from these springs is of artesian origin by the close relation observed between the yield of the warm spring B–5, which is the highest of the four springs above the river bed, and the rise of the river level. When first observed, this spring was a mere trickle of tepid water that emerged about 5 feet above the river surface. In the next two days the river rose to within about 6 inches of this spring, and two days later its yield and temperature had increased considerably. As the rise in the river level in Alcova Canyon could not increase the yield of the spring, it seems that the spring's increased yield (with a lag of two days), can be accounted for only by assuming that the rise of the river in the upper canyon increased the head on the artesian system and thus produced a greater yield in this high-level spring.

The depth reached by the water in traversing this artesian aquifer probably accounts for the elevated temperature of the water at its emergence. The Amsden formation just south of the main fault lies about 2,600 feet below the river level, which

[2] In one bore hole (C–3) drilled upstream a little way from the dam site in October, 1929, the hot water emerged with a head of 38 feet. This indicates that there is an additional supply of water being added to the artesian system—perhaps surface water entering the outcrop of the Amsden formation above the river level on the ridges, through which the upper canyon cuts.

might account for an increased temperature of about 43° F.[3] But as the springs have a temperature of about 129° F., or 75° F. above the average temperature of the river water, this does not account for all of the increase. Either of two explanations may possibly account for this difference. It may be that enough hot juvenile water rises along the fault zone and mixes with the river water in the artesian aquifer to heat it to the observed temperature. Or, the earth temperature gradient in the vicinity of the fault zone may be abnormally steep, due to friction of movement. The analysis of the water from hot spring B–6 shows that it contains about 3 or 4 times as much dissolved material as the river water, but in about the same proportions, except that the quantities of calcium sulphate and sodium chloride are much larger than in the normal river water at the outlet of the Pathfinder reservoir. This suggests that some of the artesian water in moving through the aquifer came in contact with the gypsum beds and apparently also some bedded salt in the basal part of the Embar formation (of local usage), probably where they are cut by the faults. The analysis does not indicate that any primary water is rising along the fault planes and mingling with the artesian water.

Effect of the Hot Water on the Rocks.—Most of the beds in the Amsden formation consist chiefly of limestone, and apparently certain channels in them have been enlarged by the solvent action of the long-continued artesian flow. In limestone bed No. 14, there are several vertical joints that have been enlarged by solution. The largest of these, in the east wall of the canyon, ranges in width from about 6 inches to 3 feet. As now exposed it is about 15 feet high, but the bed is nearly 20 feet thick and it is rather likely that the open fissure extends across the entire bed. The altered and cellular walls of these openings suggest that they were once the conduits of former hot springs at a time when the river flowed at a higher level; that is, before it had cut the canyons as deep as they now are. The presence of these comparatively large solution channels, of which a half dozen or so are now visible, presupposes others of comparable size that

[3] Assuming 1° F. increase for each 60 feet in depth.

open in the present river bed and from which hot water now flows. In other words, the observed flow from the four hot springs that emerge above river level may represent only a small portion of the total discharge of water rising along the beds of the Amsden formation. This inference is apparently borne out by the results of the exploratory bore holes into the river bed. The locations of the holes bored in 1921 as a part of the Gault preliminary survey (A–1 to A–3 and B–1 to B–2) are shown in Fig. 2 together with those drilled after the writer's report was completed (C–1 to C–12).

SIGNIFICANCE OF ARTESIAN FLOW.

Drill holes A–1 and A–2 penetrated two limestone beds and a limy sandstone bed (nos. 8, 9, and 10) at the top of the Amsden formation. Hole A–2 encountered crevices containing large flows of hot water. Hole A–3 did not reach bedrock but it seems to the writer significant that it encountered a continuous flow of hot water in passing through nearly 40 feet of unconsolidated river bed deposits, which would normally contain only cool water. This shows that a sufficient volume of hot water is discharging from crevices below the river bed to displace the cool water from the river gravels. Plainly the volume so discharged must be large. Hole B–1 penetrated a bed near the base of the Amsden but found no hot water and Hole B–2 did not reach rock in place and encountered no hot water.

Between the first of October and the end of December, 1929, after the writer's report was submitted, twelve additional holes (C–1 to C–12) were bored in the river bed to obtain more information about the bedrock upon which the dam is to be placed. As the detailed logs of these holes have been published,[4] it will suffice here to summarize the results. The holes (Fig. 2) are arranged in four lines of three holes each. The group farthest upstream (C–10 to C–12) all struck crevices or channels containing hot water 10 to 15 feet after penetrating bedrock—that

[4] Iakish, J. R., and others: Casper-Alcova Irrigation Project, Wyoming. House Doc. 674; 71st Cong., 3d sess., pp. 89–92, 1931.

is, just about at the contact of the Amsden and Tensleep. The next row downstream (C–7 to C–9) found a flow of hot water at the base of the river gravel just as the drill entered bedrock. One of the holes, C–8, struck "badly honeycombed limestone" at a depth of 104–108 feet, which would be about 20 feet below the top of the Amsden. The row of holes C–1, C–3, C–5 is along the line recommended by the writer for the axis of the dam and is also the line upon which the core wall of the earth and rock-fill dam is now to be constructed. The center hole, C–3, entered bedrock at 47 feet and penetrated 79 feet of sound rock before striking hot water at a depth of 126 feet. The other two holes have depths of only 47 and 48 feet, respectively. Each penetrated about 7 feet of sound rock and found no hot water. The last line of holes, C–2, C–4, C–6, is about 110 feet downstream from the core wall. Two of these holes went through fractured sandstone into whose crevices or joints the drilling water was lost, but the third hole struck a crevice about 8 feet below the surface of bedrock from which a good flow of hot water can be obtained. Apparently moderate flows of hot water through mechanical fractures or joints, as in the sandstone, can be checked by adequately grouting the sandstone below the core wall where it is planned to put grout holes on five foot centers.

The large flows of hot water found in the holes that penetrated the Amsden, together with the position of the hot springs B–4, B–5, B–6, and B–8, and the openings in the Amsden beds higher in the canyon walls, led to the conclusion that all these openings are probably connected by a system of channels in the Amsden formation. Also that part of this system of channels below and near the level of the river carries a considerable volume of artesian water which entered these beds several miles upstream where the river crosses them. According to this interpretation, a dam placed anywhere in Alcova Canyon upstream from the site of the drill holes A–1 to A–3, that is, within the area where the Amsden formation is exposed, could not prevent the by-passing of a large volume of artesian water through the Amsden formation either around the ends of the dam or under it. Indeed, a dam so placed

would considerably increase the artesian flow by increasing its head. For example, a dam about 170 feet high placed near the site of drill holes B–1 and B–2 would raise the water level about 110 feet in the upper canyon at the intake of the artesian system where the river crosses the Amsden formation. Water flowing through the larger channels in the Amsden formation with that head would probably enlarge them still more and before long cause an intolerable loss of water. The holes in the walls of Alcova Canyon connecting with this artesian system could readily be stopped, but in order to stop the artesian flow it would be necessary to resort to the obviously impracticable expedient of paving the river bed and walls of the upper canyon to a height of about 110 feet where it crosses the Amsden formation at least, and perhaps also where it crosses other adjacent formations.

THE DAM SITE.

General Statement.—In the writer's opinion the only way to avoid this likelihood of excessive loss through channels fed by artesian flow is to locate the dam downstream, below all the probable outlets of the artesian system.

A dam placed approximately 500 feet downstream from the place where the top of the Amsden formation meets the river, as indicated on Fig. 2, by an axis line and sites of the drill holes R–1, R–2, etc., will probably fulfill the necessary conditions to prevent loss of water by artesian flow. Apparently all, or at least the dominant part of the artesian flow, is restricted to the Amsden formation and possibly also other beds below the Amsden. None of the present flowing springs emerge from the Tensleep sandstone and no openings of ancient springs were found in the Tensleep. This site was chosen far enough downstream so that at a depth of about 50 feet below the river surface there would be a bed of Tensleep sandstone about 50 feet thick on which to seat the dam (Fig. 4). The statement that the river has at some time cut its channel in solid rock in this part of the canyon about 50 feet below the river surface is based on the depth to which the exploratory drill holes had to go before reaching bedrock.

Foundation and Abutment Rocks.—At this site both the foundation and abutment rocks are of sandstone which is fine-grained, even textured and rather soft and friable. Many of these beds have a weak limy cement. By comparison of these sandstone beds with a sample from a similar sandstone bed in the Amsden formation whose crushing strength was determined by the U. S. Bureau of Standards to be approximately 10,800 pounds per square inch, it seems probable that they would have crushing strengths of the order of 10,000 pounds per square inch. Such weakness necessitates a wide-base type of dam. It is likely that a fifty-foot bed of this sandstone will permit seating the dam deeply enough to resist the thrusts as required and yet leave a considerable thickness of sandstone between the dam foundations and the top of the Asmden formation. This sandstone is quite porous but its fine grain would render it sufficiently impervious so that a 35 to 40-foot bed would be an effective barrier to leakage. Despite this sandstone layer between the base of the dam and the top of the Amsden formation, and although large solution channels would not be expected in the Amsden so far below the river channel, there undoubtedly are joints and rather broad openings between beds in the Amsden formation below the dam site which connect with the reservoir and would therefore transmit an upward thrust equivalent to the hydrostatic head of the impounded water. It was pointed out that in designing the dam the possibility of this upthrust should be fully taken into account. The basal beds of the Tensleep sandstone have a moderate number of clean, narrow joints that should be carefully grouted because this sandstone has very little resistance to erosion, and streams of water flowing through the joints would soon enlarge the channels so as to endanger the structure.

As abutment rock, these massive sandstone beds should be strong enough to stand considerable lateral thrust and should be entirely satisfactory if the wings of the dam are let back several feet into solid fresh rock. Aside from the relatively few clean, tight joints that would require careful grouting, these sandstone beds should be adequately impervious because they are fine-grained and are all cross bedded on a large scale.

Spillway.—As the sandstone in this part of the canyon is easily eroded by running water, it was recommended that the spillway should be designed accordingly. So also it was recommended that tunnels in the canyon walls should be lined, and that the irrigation canal where it leads out from the reservoir and is cut into the Tensleep sandstone should be similarly protected against erosion.

The Reservoir Site.—The low saddle a little less than one mile southeast of Alcova Canyon is the only place in the reservoir site where there is danger of leakage (Fig. 1). A rather large east-west fault passes through this saddle. On the south side of it the Morrison, Sundance, and Chugwater formations have been dropped so that they now rest against the Embar formation (of local usage) on the north side. The beds of that formation dip generally southeastward toward the fault around the nose of the anticlinal arch that plunges southeastward. But as the anticline is cut off close to the saddle by the east-west fault, the dip of the so-called Embar beds is greatly steepened by the downward drag along the fault (Fig. 5). That part of the Embar forma-

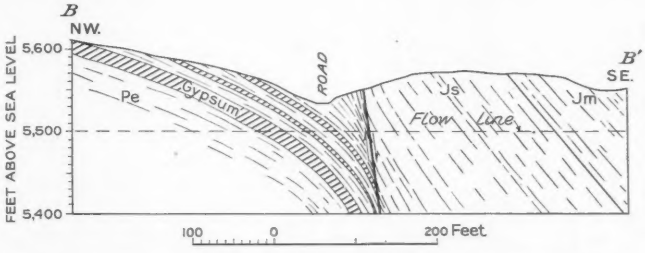

FIG. 5. Diagram showing the interpretation of the geologic structure across the saddle where the Alcova-Medicine Bow road enters the reservoir basin. *Jm*, Morrison formation; *Js*, Sundance formation; *Pe*, Embar formation (of local usage). Section taken along the line B–B′ shown on Fig. 1.

tion exposed in the saddle and along the road a few hundred feet west of it contains many beds of gypsum, one of which is nearly 17 feet thick. Thus, where most steeply inclined adjacent to the fault, the gypsum beds trend nearly transverse to the narrowest

part of the ridge that would make the divide between the reservoir and the valley of a small creek that drains into the North Platte River downstream from the dam site (Fig. 1). Furthermore, the flow line of the reservoir (5,500 foot-contour) would be high enough to come in contact with these gypsum beds. Hence, as gypsum is readily soluble and as these beds of gypsum trend across a narrow ridge, they present a real danger of leakage. Moreover, these beds of gypsum are interbedded with soft, easily eroded, sandy shale, and a flow of water once started across the divide along the gypsum beds would rapidly cut a large channel and so drain a considerable part of the reservoir. This danger could be overcome by blanketing the outcrop of the gypsiferous beds with some kind of impervious material, which in turn should be protected against wave erosion.

In addition to the protection against leakage along the gypsum beds on the north side of the fault, the ridge southeast of the saddle (Fig. 5) should be protected against wave erosion for a distance of about 500 to 600 feet, since it is narrow and consists of the soft, easily eroded shale and mudstone of the Morrison and Sundance formations. Although the beds of these formations are soft, they are essentially impermeable and dip toward the basin so that they only need protection against wave cutting to provide a satisfactory reservoir wall.

CONCLUSIONS.

The observations recorded in this paper lead to the conclusion that the Amsden formation, which makes an arched core in the central part of the Alcova Canyon ridge, contains a system of connecting channels probably capable of conducting a rather large volume of water. The lower part of this system of channels now contains a considerable flow of hot water that emerges near the river level in four hot springs on the east bank of the canyon and from crevices in the rock below the river level, some of which were cut by the test bore holes put down in 1921 as a part of the Gault preliminary survey. Most of this water is artesian and enters the channels in the Amsden formation about 5 miles upstream, where the river crosses the uptilted edges of the Amsden

formation in the upper canyon. From there the water goes down along the Amsden beds to a depth of about 2,600 feet and then rises along the same beds where they rise to make the arch of Alcova Canyon ridge. The hydrostatic head on these springs at the river level is about 22 feet. The water is heated during its passage through the rocks at depth.

A dam placed anywhere in Alcova Canyon within the area where the Amsden formation rises above the river level (Fig. 2) would, by raising the water level upstream, especially in the upper canyon, increase the head on this artesian flow and materially increase the discharge under the dam, or lower downstream by passage through the channels in the Amsden beds, which have an irregular circuitous course in the canyon walls and below the bed of the river. Discharge of water with this head through the channels in the Amsden would probably soon enlarge them and result in an excessive loss of water.

In order to avoid the possibility of this loss or the possibility of danger to the dam if it were placed over the exit of some part of this artesian system, the core wall of the dam is to be placed downstream, below the lowest probable outlet of the artesian system. The approximate position of this site is marked on Fig. 2 by an axis line, and the locations of the drill holes, R–1 to R–6, recommended by the writer.

A dam located at this site will have for its foundation and abutments the massive or cross-bedded, fine-grained, and even-textured sandstone of the Tensleep sandstone. It is judged that this rock has a crushing strength not exceeding 10,000 pounds per square inch. These sandstone beds, by reason of their fine grain and cross bedding, should be sufficiently impervious; nevertheless, both the foundation and abutments must be carefully grouted to seal all possible joints and channels, because the rock has extremely little resistance to erosion by flowing water.

Because the rock in this part of the canyon is so easily eroded, spillways, tunnels, and canals will have to be protected so as to avoid undermining structures or starting serious leaks.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.

PYRITE OXIDATION.

GEO. W. BAIN.

A STUDY of pyrite in building stone became imperative in a certain white marble, which developed an orange-colored stain in many installations where it had been used in monuments and exterior building construction. The trouble did not appear in every installation and some doubt existed as to whether the trouble was due to the stone or to construction materials used in connection with it. Examination of the marble showed a fine dark veining, which microscopic study showed to be pyrite. The stain was charged against the pyrite in the stone; yet it was known that the pyritic marble did not develop the orange discoloration in every installation. Investigation of the stained occurrences indicated that Portland cement had been used in every instance. Investigation of the unstained installations indicated that Portland cement had never come in contact with the marble.

General Features of the Stain.—The time interval for the stain to develop, distribution of the stain, and necessary accompanying materials, furnish an extensive amount of information upon the weathering of pyrite which seems worthy of note. Successful prevention of the stain is of importance to many stone companies. The orange-colored stain appears over an indefinite area six weeks after the stone comes in contact with moist Portland cement; if the days are warm and the rainfall average for a humid region, the stain is never more than three days later or earlier than the six weeks average. The stone in which staining develops has low absorption (0.14 per cent.) but does absorb ground moisture for two and in rare cases four feet above the ground or a masonry joint. The top of the stain corresponds to the top of the zone of groundwater penetration (Fig. 1-A). The bottom of the stain is four to eight inches above the ground and seems to correspond to that part which is kept cool by conduction. Stones set

in the soil never develop discoloration, so that groundwater itself never causes the stain to develop; Portland cement is the only common material that gives something to the water which will initiate the trouble. Intensity of stain increases with the length of time it forms, but the depth is slight and stone 1/16 inch below the surface rarely shows any change.

General Results of Experimental Study.—Experimental stones set on Portland cement developed the orange stain as in the case of actual installations. Check stones were watched carefully, and a greenish darkening was evident at the end of four weeks; after six weeks this greenish darkened area became decidedly orange. The amount of material leached from the Portland cement was extremely slight but gave an alkaline reaction. A great variety of salts were introduced into an equal number of test pieces to see whether any produced an effect analogous to that of the cement. Of the wide range investigated, only sodium carbonate and hydroxide and the corresponding potassium salts caused the discoloration to appear. They produced the stain in approximately the same time and place as would have been anticipated from Portland cement installations. Therefore, oxidation of pyrite is attributed to alkalies rather than to groundwater acids.

The greenish darkening, which appears at the end of four weeks, suggests ferrous sulphate, and the diffused distribution of the stain shows that insoluble ferric hydrate is not formed directly from the pyrite. Oxidation to ferrous sulphate under the influence of the alkalies seems to occur throughout the stone, and the sulphate is oxidized to ferric sulphate and the hydrate as it reaches the heated surface. Discoloration was stopped completely in stones under observation when barium chloride was introduced into the groundwater from Portland cement as it entered the stone; and so the intermediate sulphate stage seems confirmed (Figs. 1-B, 2).

Some years ago, L. D. Strong undertook to measure the electric resistance of a number of minerals as a subject for an honors thesis at Amherst College. In the course of the work he found

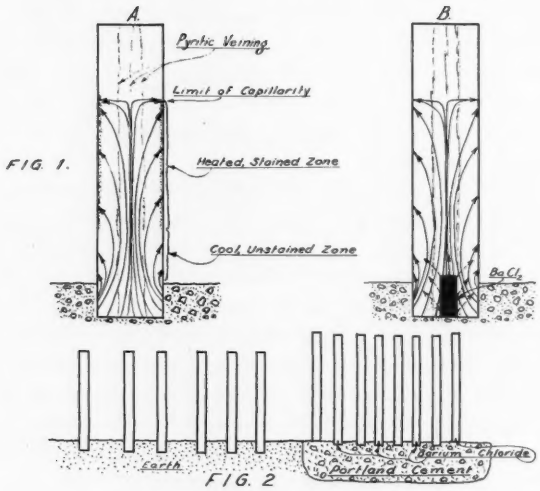

FIG. 1.

FIG. 2

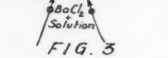

FIG. 3

FIG. 1. Diagram of path of groundwater in stone set in concrete. *A*. Untreated stone. The stained zone occurs between the upper limit of rise of groundwater by capillarity and the lower cooled zone, and discoloration is limited to the outer surface; it is distant from pyritic veining in many instances. *B*. Treated stone. Crystals of a soluble barium salt (black) are placed in the base of the stone. Groundwater dissolves some of the salt and carries it along.

FIG. 2. Diagram showing arrangement of test pieces, in an experimental set, placed under conditions as nearly identical as possible. Every untreated piece on or in concrete developed a stain after six weeks. No treated piece or piece set in the soil showed any sign of stain after three years.

FIG. 3. Diagram showing barium sulphate (black) precipitated on an irregular pyrite grain. The stable ferrous chloride is believed to reach the surface of the stone and pass off in rainwater. Greater stability of the chloride over the sulphate accounts for the success in stone treatment.

that pyrite belonged to two varieties; one had a resistance of less than an ohm per centimeter and the other a resistance exceeding 10,000 ohms per centimeter. The highly conducting variety weathered very much more rapidly than that of high resistance; also no pyritohedral forms were observed on any of the conducting specimens. The white marble which developed stains was observed to contain the conducting variety of pyrite. Pyritohedral pyrite from parts of the marble deposit has been left in contact with Portland cement for long periods and shows no tendency to weather to the sulphate and distribute as an orange discoloration. The pyrite conductivity tests need more extensive verification, and the weathering features associated with conducting pyrite need closer checking, but the observations suggest some important features in pyrite oxidation.

Conclusions.—Oxidation of at least one variety of pyrite is accelerated by the presence of sodium and potassium salts, which give an alkaline reaction in groundwater in capillary openings in stone. The initial alteration is to ferrous sulphate and can be halted at this stage by treatment with barium chloride. Barium chloride reacts with the ferrous sulphate, forms an insoluble barite precipitate about the pyrite, and arrests alteration (Fig. 3). If the stone is untreated and the ferrous sulphate is allowed to form and migrate, it moves to the surface of the stone; the sulphate encounters a heated zone and an excess of oxygen, and changes to ferric sulphate and eventually to ferric hydrate.

AMHERST COLLEGE,
AMHERST, MASS.

THE TIN DEPOSITS OF LLALLAGUA, BOLIVIA.

F. S. TURNEAURE.

PART II.

CONTENTS—*Part II.*

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THE BONANZA ORE SHOOTS.

General Description.—The "bonanza ore-shoots" form high-grade sections of the shoots previously described. Boundaries are again gradational and arbitrary, and highly irregular in detail. Low-grade sulphide mineralization generally persists above the high-grade ore, and most bonanza shoots terminate upward within the sulphide zone! This fact is of wide significance, and it will be referred to again. In Fig. 11, for example, the vein filling of Level A, which lies above the high-grade shoot, consists of pyrite and marcasite with accessory quartz, sphalerite, and siderite.

Horizon of Maximum Value.—Although records are far from complete, the available data indicate that the major veins are characterized by a high-grade section, which includes from about one fifth to one half of the total vertical extent of the ore. The horizon of maximum value, however, bears no relation to the zone of oxidation. In most veins it is separated from the oxide zone by sulphide ore of moderate grade; in some it extends into the oxide zone from which good ore is then produced; and in a few it extends upward approximately to the bottom of the oxide zone.[25] The relationship is illustrated diagrammatically in Fig. 12.

[25] Ahlfeld (*op. cit.*, p. 255) stated that the high-grade ore horizon lies at a higher elevation at the border of the stock than at the center, a point previously made by Pilz (Metall u. Erz, vol. 22, p. 373, 1925). Field relations, however, fail to support this generalization.

Origin.—In 1926, Koeberlin [26] advanced the theory of secondary enrichment to account for the high-grade ore-shoots of certain Bolivian districts, and he referred to the Llallagua district as an excellent example of the process. Recently Singewald [27] has reviewed the evidence in a logical and convincing manner, and he has come to the conclusion that secondary enrichment of tin is not of commercial importance. The general aspects of the problem, as discussed by Singewald, need not be reviewed, but the specific evidence as it applies to Llallagua should be noted:

(1) Some bonanza ore-shoots certainly terminate upward within the sulphide zone, and they are separated from the oxide zone by *sulphide ore* of moderate grade, a zonal arrangement which is incompatible with secondary enrichment.

(2) The ore-shoot emphasized by Koeberlin as indicative of supergene enrichment belongs to an exceptional group in which the high-grade ore is close to the zone of oxidation, and in which the intervening low-grade sulphide zone is lacking or obscure. The vertical arrangement of zones is thus suggestive of supergene enrichment, but the case is a special one and not representative.

(3) Koeberlin [28] attaches considerable importance to the association of cassiterite and marcasite, the latter being regarded as of supergene origin. Microscopic study, however, shows that the association is of no compelling significance; the marcasite is consistently later in age than the cassiterite, and it is largely of hypogene origin.

(4) Banded ore of the oxide zone is comparable with that of the sulphide zone; the cassiterite forms two bands contiguous to the quartz and separated by a central band of iron oxides.

(5) The microscope records cassiterite of only one age; it precedes the iron sulphides, arsenopyrite, sphalerite, and stannite. Some tin is doubtless released in the oxidizing alteration of stan-

[26] Koeberlin, F. R.: Geologic Features of Bolivia's Tin-bearing veins. Eng. & Min. Jour., vol. 121, pp. 636–642, 1926. Discussion, *idem.*, vol. 122, pp. 502–503, 819–821, 1926.

[27] Singewald, J. T. Jr.: Problem of Supergene Cassiterite in Bolivian Tin Veins. ECON. GEOL., vol. 24, pp. 343–364, 1929.

[28] *Op. cit.*, page 640.

nite and franckeite, and Berkey and Colony [29] report a small amount of amorphous metastannic acid which is probably of this origin. Supergene cassiterite in minute quantity cannot be denied, but, at best, it is a rare vein constituent and wholly inadequate to account for the high-grade ore.

(6) Under the microscope, the cassiterite of the oxide zone shows no evidence of attack; it exhibits the same sharp boundaries, euhedral form, and granular aggregates from the deepest mine level to the surface. It may be coated by the products of oxidation, but it is not replaced.

(7) Greene [30] reports a small amount of tin in the mine water of Llallagua, but this is more likely derived from accessory stannite and franckeite than from cassiterite.

From the foregoing facts, it is clear that the bonanza oreshoots of Llallagua are hypogene; the evidence from both field and laboratory is fully convincing. Based upon a microscopic examination of the ore, the same conclusion was expressed by Berkey and Colony,[31] and more recently by Ahlfeld.[32]

HYPOGENE ZONING.

The General Picture.—The most pronounced zonal effect of the Llallagua district is the limited distribution of high-grade ore, and there is little difference between the sulphide zones above and below the high-grade section. Both are characterized by the predominance of pyrite and marcasite, and by accessory quartz, arsenopyrite, stannite, and sphalerite. To these should be added franckeite and pyrrhotite as important minerals of an earlier stage. Quartz may be more abundant below and sphalerite above the high-grade section, but the other minerals show no clear-cut zonal distribution.

Considering the district as a whole, there is a lateral zoning as well; a central cassiterite zone, and a marginal sulphide zone, the latter being similar in mineralogy to the sulphide zones of the

[29] *Op. cit.*

[30] Greene, G. U.: Eng. & Min. Jour., vol. 122, p. 417, 1926.

[31] *Op. cit.*

[32] *Op. cit.*, p. 257.

vertical sequence. However, the sulphides not only predominate in the marginal veins, but they also form countless veins within the cassiterite area. In brief, hypogene zoning has produced a high-grade cassiterite core and a low-grade sulphide shell.

The foregoing picture of hypogene zoning is in marked contrast to the one given by Ahlfeld, which was based upon a brief visit to the mine. He outlines three vertical zones: (1) an intermediate zone of cassiterite in "shoots of unexampled richness," (2) a lower zone marked by abundant tourmaline "which higher up is more restricted and disappears entirely at the surface," [33] and (3) an upper zone, or "third zone farthest removed from the magma" which is "characterized by the predominance of sulphides and sulphosalts of tin, lead, copper, antimony, and zinc. These are lacking in the lower parts of the mine and increase in abundance upwards." [34] The intermediate zone, as described by Ahlfeld, is essentially correct, but tourmaline is abundant throughout the ore deposit, tons of it having been deposited at the horizon of the present surface; and the unoxidized vein filling of the upper zone consists of pyrite and marcasite, whereas the minerals mentioned by Ahlfeld are accessories of wide distribution. To establish a zoning on the basis of their occurrence would require a far more extensive mineralogical study than any attempted thus far.

Of the three zones described by Ahlfeld, one is a reality but the other two do not exist as zones. He fails to mention the lateral variation in mineralization, and he thereby overlooks the essential zonal effect of the district; the cassiterite core and the sulphide shell.

Origin.—The zoning of the Llallagua district is of a unique type and presumably requires a combination of favorable factors rarely duplicated elsewhere. Evidence discussed later strongly suggests that the deposit was formed under a greater range in pressure and temperature than that of most ore deposits, and this unusual range, combined with a rapid release of pressure, may have been the principal factor in the development of the cassiterite core.

[33] Ahlfeld, Friedrich: *Op. cit.*, p. 255.

[34] *Idem*, p. 256.

ORIGIN OF THE ORE DEPOSIT.

The great ore bodies of the Llallagua district are of hypogene rather than supergene origin, and consequently the story of hypogene mineralization is of far greater importance than that of supergene alteration. The pertinent facts regarding hypogene deposition may be grouped under two major points, that of the mineralizing solutions and that of the environment of ore deposition. Naturally the two are interdependent, and the environment, broadly defined, conditions the temperature, pressure, and to a certain extent, the chemical composition of the ore-solution.

The Ore-depositing Solutions.

Source.—The occurrence of ore within and adjacent to the Salvadora stock is no mere coincidence; it implies that the porphyry magma and the ore-solutions were both derived from some larger igneous body which crystallized in depth. In its broader aspects, the Llallagua deposit is similar to countless others, which can be reasonably explained only on the theory that the valuable metals have been derived from magmas and have been transported to their present position by hot waters of magmatic origin.

Temperature.—A great body of empirical field data is at hand regarding the occurrence of minerals in temperature zones; thus the mineralogy of an ore furnishes the best guide to the temperature of the ore-depositing solution. In general, laboratory experiments confirm the facts of mineral occurrence, but many experiments find no counterpart in nature, and few can be applied directly to the problems of hypogene deposition.

The approximate temperature range may be fixed by the depth of ore deposition, but this is of questionable value since temperature is not always proportional to depth, especially in regions of igneous activity where ores are likely to form. A safer guide to temperature is the zonal distribution of minerals outward from an intrusive center, and those minerals which consistently appear within the high-temperature belts can be regarded with confidence as of high-temperature origin.

Considering the early minerals of Llallagua, tourmaline, cassiterite, and bismuthinite are characteristic of many hypothermal tin deposits in granite; and, in districts where a lateral zoning has been established, these minerals favor the high-temperature belts close to or within the intrusive. The early sequence also includes accessory apatite, muscovite, and monazite, minerals of high-temperature association, as well as abundant non-diagnostic quartz. It seems reasonable to conclude, therefore, that the early mineralization of Llallagua was of a high-temperature aspect, and comparable with that of other tin deposits, such as Cornwall and Saxony.

Native bismuth is of rare occurrence at Llallagua, and little is known regarding its paragenesis, except that it follows bismuthinite. Nevertheless, it is significant, for its melting point is 269° C., a temperature well below that usually assigned to the tin deposits with which it is found. To explain this association, recourse cannot be had to the possible effect of pressure; the metal expands upon freezing and an increase in pressure lowers its melting point. Most authorities regard native bismuth as hypogene, but Kittl [35] compares it with native copper and attributes it to the supergene alteration of bismuthinite. At Llallagua the native bismuth is hypogene, and its presence indicates that locally, at some stage following the deposition of bismuthinite, the temperature was less than 269° C.

The Llallagua tin deposit departs from the typical occurrence in granite in the relative abundance of franckeite, pyrrhotite, pyrite, and marcasite. The franckeite has a greater vertical and lateral range than cassiterite, and this may mean a lower temperature of deposition. Sulphosalts are commonly of low-temperature association and of late age, but this generalization can hardly be applied to franckeite; descriptions of its paragenesis are few and no clear record exists of its zonal distribution with respect to other tin minerals. Ahlfeld [36] has recorded the mineral in some 15 districts south and east of Oruro. On the basis of

[35] Kittl, Erwin: Revista Minera (Buenos Aires), vol. 2, pp. 1–4, 1930.

[36] Communication, ECON. GEOL., vol. 25, pp. 546–548, 1930. Revista Minera de Bolivia, vol. 1, pp. 145–153, 1926.

field examination, he first classified it as supergene, but after microscopic study of the ores, he grouped it with the late hydrothermal minerals of lead and silver.[37] Davy regards the franckeite of the Porvenir Mine, near Huanuni, as earlier than "stannite, sphalerite, and late pyrite," whereas Lindgren believes that it may be supergene.[38] At Llallagua, the franckeite is a relatively early hypogene mineral, but its temperature significance is problematical.

Outside of Bolivia, pyrrhotite is not a common associate of tin ores, but at Llallagua it was deposited in abundance, and in large part as a replacement of franckeite. Its existence was brief and it was soon replaced by a number of minerals, of which wolframite was perhaps the first. Both minerals are of high-temperature association, pyrrhotite occurring commonly with other base-metal sulphides and wolframite with cassiterite. In some districts wolframite is deposited somewhat farther from the intrusive center than cassiterite,[39] but in many tin deposits the two are intimately associated and of about the same age.

Sphalerite, stannite, arsenopyrite, and pyrite are not individually diagnostic, but, as a group, they may reflect a reduction in temperature following the deposition of cassiterite. Base-metal sulphides occupy a marginal position to cassiterite in a number of districts,[40] and the same is true of stannite in the Mt. Heemskirk-Mt. Zeehan field of Tasmania.[41] On the other hand, the cockade ores of Chocaya, Bolivia,[42] exhibit a repeated banding of cas-

[37] *Op. cit.* Also Zeit. prakt. f. Geol., vol. 35, pp. 81–85, 1927; vol. 36, p. 43, 1928.

[38] Davy, W. M.: Ore Deposition in the Bolivian Tin Silver Deposits. Econ. Geol., vol. 15, pp. 463–496, 1920. Also see note by Singewald, J. T., Jr.: *Idem*, vol. 16, p. 49, 1921. Lindgren, Waldemar: *Op. cit.*, p. 657.

[39] Jones, W. R.: Economic Significance of Relative Temperature of Formation of Tin and Tungsten Deposits. Inst. Min. & Met. Trans., vol. 29, pp. 320–376, 1920.

[40] Emmons, W. H.: Relation of Metalliferous Lode Systems to Igneous Intrusions. Trans. Amer. Inst. Min. Eng., vol. 74, pp. 29–70, 1926. Davison, E. H.: Zonal Arrangement of Minerals in the Cornish Lodes. Econ. Geol., vol. 22, pp. 475–480, 1927. Berg, G.: Zonal Distribution of Ore Deposits of Central Europe. Econ. Geol., vol. 22, pp. 113–133, 1927.

[41] Twelvetrees, W. H., and Ward, L. K.: The Ore-bodies of the Zeehan Field. Tasmania Dept. Mines, Geol. Survey, Bull. 8, p. 164, 1910.

[42] Buerger, M. J., and Maury, J. L.: Tin Ores of Chocaya, Bolivia. Econ. Geol., vol. 22, pp. 1–13, 1927.

siterite, pyrite, stannite, and chalcopyrite; a texture which is usually interpreted as the result of minor oscillations rather than of extreme changes in temperature.

Hypogene marcasite is almost entirely confined to low-temperature deposits, and its occurrence in great quantity at Llallagua is an indication that moderate to low temperatures prevailed during the late stages of mineralization. The marcasite is followed by pyrite, siderite, sphalerite II, and chalcopyrite, persistent minerals which are compatible with a late, low-temperature episode of mineralization. Arsenopyrite is characteristic of the intermediate and high-temperature deposits, but its occurrence at Llallagua as an accessory mineral in part later than marcasite is not without parallel, for it is reported from some gold-silver veins and from many stibnite deposits of low-temperature origin.

Thus far sericite has not been mentioned. In general, it is more common in mesothermal than in hypothermal ores, and granting that it represents a lower temperature of deposition than tourmaline, it may belong to an early period of rising temperature, or to a late period of declining temperature. Its position in the sequence is not accurately known.

In summary, the Llallagua mineralization corresponds to a temperature range which is generally represented by several deposits, but the series is here compressed into a single occurrence. Without assigning exact limits, the early mineralization is of the high-temperature type, as shown by tourmaline, cassiterite, bismuthinite, and apatite; whereas the late mineralization is of the low-temperature type, as suggested by the unusual abundance of sulphides, and, more definitely, by the pronounced development of hypogene marcasite. Temperature change was probably not uniform; the native bismuth and franckeite may reflect an intermediate period of low temperature, and the replacement of franckeite by pyrrhotite a subsequent period of rising temperature.

Pressure.—The mineralogy of an ore gives little information in regard to solution pressure, and other factors must be evaluated in this connection, of which the environment of ore deposition is the most important. If solution pressure were simply hydrostatic, it would be fixed by the depth at which the ores were formed, but

it is a variable, largely dependent upon the origin and subsequent history of the solution itself. As the crystallization of the parent magma proceeds, the internal pressure of the residual fraction increases until it exceeds the external pressure, when the solutions begin to move upward and outward; and, in the absence of favorable channelways, the pressure of the solution may be well in excess of the hydrostatic head.

To anticipate the discussion, it may be noted that the Llallagua ores were formed comparatively close to the surface, under lava flows and volcanics which were later removed by erosion. The near-surface zone is commonly referred to as one where open fractures control mineralization, and where the solution pressure can be calculated on the basis of the hydrostatic head. But this hardly takes into account all pertinent facts. Within a volcanic region, the solution pressure may be high in the initial stages of mineralization, due to the "boiler-plate effect" of the overlying volcanics,[43] but later, when the rocks are thoroughly fractured and channelways to the surface are established, the pressure will be greatly reduced, and final deposition may take place at a pressure hardly more than the hydrostatic head. However, as Graton [44] points out, the pressure release would not be a single event of brief duration, but a continuous process affecting the solutions as they worked their way from a high-pressure zone of restricted channelways into a low-pressure zone with a network of fractures. A sufficient change in pressure might cause a vaporization of the solutions, and the consequent wholesale deposition of minerals within a restricted vertical zone.[45] That is, a vapor phase is suggested as an important agent of deposition, and not as an agent of transportation.

Applying the foregoing theory to Llallagua, the deposition of tourmaline may reflect an initial high-pressure stage; the formation of cassiterite, a mineral of restricted distribution, may be coincident with the period of maximum change in pressure; and the

[43] McLaughlin, D. H. Personal Communication.

[44] Graton, L. C. Personal Communication.

[45] Graton, L. C.: The Depth-zones in Ore Deposition. ECON. GEOL., vol. 28, p. 544, 1933.

widespread deposition of sulphides may mark the final period of low pressure and reduced pressure gradients. The intensity of fracturing is probably less in the lower mine levels than it is at the horizon of high-grade ore, and this lends support to the view that pressure has played an important rôle.

Chemical Character.—In regard to tin deposits generally, two opposing theories of origin have been advanced; the one compares them with deposits of volcanic craters, and fumaroles; the other with the more common type of vein composed of sulphides, quartz, and carbonates. The first, generally referred to as the "pneumatolytic theory," assumes deposition by acid magmatic extracts in the form of gases; the second, deposition by residual hydrothermal solutions of alkaline type, but probably at a temperature above the critical temperature of pure water. The Llallagua deposit offers some evidence regarding ore-solutions in general, and it supports the view that tin-depositing solutions are fundamentally the same as those which account for quartz veins, base-metal deposits, and ores of gold and silver.

The pneumatolytic theory has been emphasized recently by Vogt,[46], and Niggli,[47] and both authors agree that the complete crystallization of a magma includes three contrasting stages: (1) magmatic, (2) pneumatolytic, and (3) hydrothermal. According to Vogt, tin, tungsten, bismuth, boron, etc. are extracted from the magma as volatile fluorides at an early stage of crystallization, and these metals are subsequently deposited from the acid gases, and not from the residual liquids which form the gold-quartz veins and base-metal deposits. Niggli likewise believes that the pneumatolytic solutions are distinct from the hydrothermal, but in the gaseous state only if the external pressure is comparatively low. He refers the tin deposits in granite to a zone of considerable but not excessive depth where gases are likely to exist. "The true deposits of the cassiterite pneumatolysis show characteristics that on the whole suggest a process of for-

[46] Vogt, J. H. L.: Magmas and Igneous Ore Deposits. ECON. GEOL., vol. 21, pp. 209–234, 309–333, 468–498, 1926.

[47] Niggli, Paul: Ore Deposits of Magmatic Origin. Transl. by H. C. Boydell, London, 1929; Die Leichtflüchtige Bestandteil in Magma. Leipzig, 1921.

mation dependent on a vapor phase rich in fluorides, sometimes also in chlorides." [48]

In connection with the pneumatolytic theory, the detailed investigations of the acid fumaroles of Katmai and the acid spring deposits of Mt. Lassen are of special interest. The fumaroles of Katmai [49] consist largely of steam with a small proportion (0.5 per cent) of acid gas. High-temperature vents are marked by incrustations of magnetite, and by "banded opal impregnated with a complex mixture of chlorides, sulphates, and fluorides"; low-temperature vents by sulphur and pyrite with a little arsenic, selenium, and tellurium. The principal metal deposited is iron, which is transported largely as chloride. The sediments of the weakly acid springs of Mt. Lassen [50] consist of silica, kaolinite, alunite, sulphur, and pyrite.

Day and Allen believe that acid springs are the natural consequence of the dilution of acid fumaroles by meteoric water; and that alkaline springs represent either acid waters modified by reaction with the wall rock, or meteoric waters mixed with fumaroles which contain practically none of the acid-forming constituents. These conclusions, however, are based upon the fundamental idea that "if water is to leave the magma at all it must do so as steam." [51] The gases are then acid for they can readily dissolve the acid constituents, but not the alkalies and other bases which volatilize at high temperature.

The accurate data regarding the Mt. Lassen and Katmai activity, and the actual deposition of metals by gases cannot be questioned, but undoubted examples of such deposition come from the shallowest zone, that of the surface, where the external pressure is at a minimum and where the gases are free to escape. To compare such deposits with the great ore concentrations is open to serious objection, since the latter represent earlier and far deeper manifestations of igneous activity.

[48] *Idem*, p. 37, 1929.

[49] Zies, E. G.: The Fumarolic Incrustations and Their Bearing on Ore Deposition. Nat. Geog. Soc. Tech. Papers, Katmai Series, vol. 1, No. 4, pp. 1–61, 1929.

[50] Day, A. L., and Allen, E. T.: The Volcanic Activity and Hot Springs of Lassen Peak. Carnegie Inst. of Wash. Pub. No. 360, 1925.

[51] *Idem*, p. 164.

The common ore solution is essentially the residual fraction of an alkaline magma, and it produces a mineralization which indicates pretty clearly that the solution is liquid rather than gaseous, and alkaline rather than acid.[52] Vein fillings and metasomatic products, in endless variety, give evidence of the tremendous interchange of material; of the transfer not only of the volatile metals but also of the highly refractory alkalies. Liquid solutions are adequate transporting agents, but not steam with a minor quantity of acid gas. The temperature and pressure may be high, but still well below the critical temperature of the complex solution, a point emphasized by Morey,[53] who concludes that "in natural magmas critical phenomena probably play no part." Day and Allen[54] agree that if the solution be liquid, then the acid components, although more concentrated than in the magma, would be inadequate to neutralize the strong bases. In short, the magmas are certainly alkaline, and liquids produced by their crystallization are probably alkaline.

The low transporting power of vapors is a serious objection to the pneumatolytic theory as applied to tin deposits. It is true that minerals of the greisen reflect additions of chlorine, fluorine, and boron, but their deposition involves an even greater interchange in the bases. The so-called "pneumatolytic" minerals may be absent or, as at Llallagua, they may be independent of tin deposition both in time and place. The small proportion of volatiles in such minerals is no more an argument in favor of a strong gas phase than is the fluorine in fluorite, or the carbon dioxide in calcite. Finally, those who favor the pneumatolytic theory have failed to show in what fundamental way the pneumatolytic deposits differ from those of hydrothermal origin.

The foregoing arguments are not new, and many additional facts opposed to the theory have been cited, but they need not be repeated here. The typical tin mineralization belongs to an early

[52] Lindgren, Waldemar: Mineral Deposits, 3d Ed., pp. 140–43, 732–735. Ross, C. S.: Physicochemical Factors Controlling Magmatic Differentiation and Vein Formation. ECON. GEOL., vol. 23, pp. 864–886, 1928.

[53] Morey, G. W.: Relation of Crystallization to the Water Content and Vapor Pressure in a Cooling Magma. Jour. Geol., vol. 32, pp. 291–295, 1924.

[54] *Op. cit.*, p. 165.

stage in the history of the residual liquid solution, and solubility relations are such that certain high-temperature silicates, containing a small proportion of "volatiles," are likely to be precipitated during this early stage.

It is clear from the preceding discussion that the principal mineralization of Llallagua was effected by alkaline liquid solutions; the variety of tourmaline indicates an important addition of magnesia, and the abundant sericite requires the wholesale substitution of potash for soda and lime, results which can be accomplished far more readily by liquids than by gases. Furthermore, Llallagua is similar to the accepted hydrothermal deposits in many respects; base-metal sulphides are abundant, the ore occurs in well-defined fractures, and the mineralogy of the wall rock contrasts with that of the vein filling. The widespread deposition of sericite in the porphyry demands a solution with a power of penetration fully as great as that which deposits tourmaline or topaz in granite.

The foregoing theory of origin is directly opposed to the pneumatolytic theory advocated by Ahlfeld.[55] He believes that the mineralization of Llallagua "suggests very concentrated acid solutions with strong gas phase, and temperature of 400° to 500° C.," but the only evidence cited in favor of this view is the occurrence of certain "type" minerals such as tourmaline, and apatite, and of well-crystallized rather than of fibrous cassiterite. Native bismuth is included as a part of the pneumatolytic phase, although it melts at 269° C. Ahlfeld records no important textural difference between the "pneumatolytic" minerals and those which he regards as of hydrothermal origin, nor any difference in their mode of occurrence in the field. In short, Llallagua may include an unusual mineral assemblage, and it may have formed at a high temperature; but there is no valid reason for assuming that it is of "pneumatolytic" origin, to be sharply distinguished from the hydrothermal deposits of other metals.

The unusual abundance of hypogene marcasite points to an important change in the chemical character of the ore solution

[55] *Op. cit.*, p. 257.

during mineralization. Laboratory experiments show that a mixture of pyrite and marcasite is precipitated in acid solutions, and pyrite alone in alkaline solutions.[56] These results agree with the field distribution of the two minerals, pyrite being the common hypogene sulphide and marcasite the principal supergene mineral. Hypogene marcasite is known but is almost entirely confined to deposits of the near-surface zone, where the ore-solutions are more nearly comparable with those of the acid fumaroles, and where the marcasite is locally associated with alunite and kaolinite, both of which are known to occur in the sinters of acid springs. At Llallagua, the marcasite is almost contemporaneous with the typical hypogene minerals, pyrite and arsenopyrite, from which it may be inferred that the solutions were neither strongly acid nor at a high temperature, for the high-temperature precipitation of marcasite requires high acidity.

A second feature of the Llallagua deposit is the almost complete elimination of pyrrhotite by late hypogene solutions. The mineral is known to be readily attacked by acid sulphate waters of surface origin, and if the hot hypogene solutions became acid during mineralization, an even greater destruction of the pyrrhotite would likely occur.

The stability relations of wurtzite and sphalerite are comparable with those of marcasite and pyrite; sphalerite is precipitated from alkaline solutions and wurtzite from acid solutions above a certain concentration.[57] At Llallagua the marcasite, in part, is followed by arsenopyrite and pyrite, and by sphalerite II rather than by wurtzite, a sequence which suggests reversals in the chemical composition of the ore-solution rather than a constantly increasing acidity.

The change from alkalinity to acidity is, fundamentally, a change from sulphide to sulphuric acid. Surface oxidation can hardly apply to ascending solutions at a depth of two or three thousand feet, and the oxidation effect of ferric iron can be ruled

[56] Allen, E. T., Crenshaw, J. L., and Merwin, H. E.: Effect of Temperature and Acidity in the Formation of Marcasite and Wurtzite. Amer. Jour. Sci. (4), vol. 38, pp. 393–432, 1914.

[57] *Idem*, pp. 421–426.

out since ferric minerals are not abundant in the altered Salvadora stock. The gradual depletion of strong bases tends toward reduced alkalinity, but this process alone could hardly produce a solution with an excess of acid. A more reasonable explanation has been noted by Graton.[58] In the precipitation of metals from polysulphide solutions, free sulphur is produced, and at certain temperatures this reacts with water to form sulphuric acid.

To a minor degree, strong acid radicals are fixed in high-temperature minerals, but it is significant that the salts of strong acids, such as fluorite, alunite, and barite, are more common in ore deposits of the near-surface zone, and that sulphates, chlorides, fluorides, and borates characterize the deposits of fumaroles and hot springs. In the early and principal stages, the ore-depositing solutions are almost certainly alkaline, but mineral association suggests that in a favorable near-surface environment they may become acid.

At Llallagua, the normal tendency toward decreased alkalinity was accentuated, and in the late stages of mineralization, coincident with the deposition of marcasite, the depleted solutions became neutral or weakly acid and, in a way, comparable with the acid fumaroles. Such a change would not be expected at the depth represented by tin deposits in granite, but is not entirely out of place at Llallagua, since other facts indicate that the ores were formed in the near-surface zone.

The Environment of Ore Deposition.

The geological environment of ore deposition may be defined to include the original depth at which the ores were formed, and the relation which the ore deposit bears to the larger magmatic province. The temperature, pressure, and chemical composition of the ore solutions have been evaluated on the basis of the net results of mineralization, but the conclusions should be consistent with the geological environment as determined by other lines of evidence.

Depth of Ore Deposition.—The Llallagua district forms but a

[58] *Op. cit.*, p. 541.

part of the highly mineralized belt of Central Bolivia, which includes Potosi, Oruro, Colquechaca, Huanuni, and many other districts. This region is characterized by a silver-tin metallization in genetic association with small quartz-porphyry stocks and "volcanic vents," and it stands in marked contrast to the mineralized belt of the Cordillera Real farther north, where tin deposits without silver are clustered about granitic intrusives. At Oruro and Potosi, Lindgren [59] places the depth of ore formation at about 1000 feet, and the many points of similarity between these deposits and others of the Central belt indicate that the region as a whole is one of shallow mineralization. Although at Llallagua the local physiography suggests a somewhat greater depth than the figure given by Lindgren, the ores were probably formed within the near-surface zone.

Volcanic formations genetically related to the Salvadora vent probably covered the Llallagua district at the time of ore deposition, but similar formations in southern Bolivia [60] are rarely more than a few hundred feet thick. At Llallagua the volcanics have been removed, and a surface of considerable relief has been carved in the underlying sedimentary formations. The evidence does not allow a close estimate of the amount of erosion, but a maximum of some three thousand feet appears reasonable.

The intrusion of the Salvadora stock was closely followed by fracturing and ore deposition. In other words, the crystallization of the magma, the formation of the fracture system, and the deposition of ore all took place within the same depth zone. As already explained, the stock represents a near-surface vent, and the veins in size, spacing, and structure are comparable with others of near-surface development; facts which directly confirm the near-surface origin of the ore, whereas structures typical of the deep vein zone are notably absent.

The Potosi veins cut plant-bearing beds of late Miocene or

[59] Lindgren, Waldemar, and Abbott, A. C.: The Silver-tin Deposits of Oruro. ECON. GEOL., vol. 26, pp. 453–480, 1931. Lindgren, Waldemar, and Creveling, J. G., *op. cit.*, pp. 233–262.

[60] Lindgren, Waldemar: ECON. GEOL., vol. 23, p. 258, 1928; Ahlfeld, Friedrich, Neues Jahrb. f. Min., Beil. Band 65–A, 1932, Plate 50.

Pliocene age, and, in view of the close similarity in geological setting, it seems reasonable to assign a similar age to the tin veins of Llallagua. Age, in itself, is rarely a guide to the depth of ore deposition, but few, if any, deposits of such late age are found in the mesothermal division. In the great belts of middle and late Tertiary volcanism, erosion has not yet reached the mesothermal zone, although it has perhaps approached that zone in a few districts.

The textural and mineralogical criteria of the three depth zones of the hydrothermal sequence have been clearly summarized by Lindgren,[61] and in a number of respects Llallagua corresponds to the near-surface deposits. Banding and crustification are common, the ore is largely confined to the fractures, the filling is commonly frozen to the vein walls, and drusy cavities are abundant. The microscope reveals fine-grained aggregates, delicate textures, intricate pseudomorphs, and complex replacements. On a larger scale, the ore occurs in shoots of high grade but of limited extent, a feature which is particularly characteristic of near-surface deposition.

In mineralogy, however, the Llallagua tin deposit is in striking contrast with those usually grouped in the near-surface zone; the ore is tin rather than gold, silver, or mercury; tourmaline and cassiterite are abundant; chlorite, barite, and carbonates are subordinate or entirely absent. On the basis of this mineralogy, the deposit would be classed as hypothermal, but in hypothermal deposits franckeite is unknown and marcasite is rare. In short, the mineralogy conforms strictly to neither the epithermal nor the hypothermal divisions, and it reflects a temperature range which exceeds that of most ore deposits.

Except in mineralogy, the Llallagua tin deposit is in agreement with near-surface mineralization, and, in view of this conflicting evidence, either one of two explanations must be chosen: (1) mineralogy is not a safe guide to temperature, or (2) relatively high temperatures may prevail within the near-surface zone. For reasons given presently, the second alternative is favored and

[61] Lindgren, Waldemar: Mineral Deposits, 3d Ed., pp. 516–538, 598–615, 718–735.

Llallagua is regarded as a high-temperature deposit of the near-surface, volcanic environment.

Relation between Llallagua and the Larger Magmatic Province.—A consideration of the geology of the region from Oruro southward shows that Llallagua was but one of several centers of volcanic activity in late Miocene or Pliocene time, and that lava flows or tuff beds then covered much of the territory of the present Eastern Cordillera. Ore deposition at Llallagua and elsewhere was but a phase of this magmatic activity, and it took place in a distinctly volcanic environment, although most of the ores exploited to-day were deposited beneath the surface volcanics. The pressure which is likely to exist in such an environment has already been discussed, but what may be inferred as to the temperature?

During the rather extended period of volcanic activity, surface temperatures are far above normal; lava flows are crystallizing at high temperature, fumaroles are active, and boiling hot waters issue at the surface. Rocks cool slowly and, for that reason, abnormal temperature gradients exist over large areas, being especially pronounced at volcanic centers where intrusives extend to great depth. Ore deposition forms but a part of the magmatic cycle, and it might take place in surface volcanics with important residual heat. The "pre-heating" of solution channelways would help to maintain the solutions at a high temperature until they reached the near-surface zone, where the extremely steep temperature and pressure gradients would lead to rapid precipitation, with the formation of restricted ore-shoots of a complex type.[62]

It is evident that the broad picture of mineralization at Llallagua agrees well with that of the near-surface, volcanic environment. The minerals of the ore reflect an unusual range in temperature, the abundance of marcasite suggests an approach toward the acid fumarole stage of the magmatic cycle, the complexity of mineralization points to relatively complete and rapid precipitation, and the restricted ore-shoots and the unique hypo-

[62] Graton, L. C., *op. cit.*, pp. 544–545.

gene zoning seem to require an extreme variation in pressure. Ore deposition closely followed the intrusion of the Salvadora stock, and the heat of that body, with its small cross-section, could easily produce the required gradients, with the principal deposition taking place within a restricted, but peculiarly favorable, zone.

If the epithermal gold and silver deposits are considered to be of a low-temperature type, then high-temperature deposits are comparatively rare in the near-surface zone. The reason for this touches highly speculative points; the time interval between intrusion and ore deposition, the directness of solution channelways and their location with respect to igneous bodies with residual heat, and the distance from the point of origin of the ore solution to the point of ore deposition.

SUMMARY.

In the Llallagua district, the intrusion of the Salvadora quartz porphyry, the formation of the complex fracture system, and mineralization were closely related events. The Salvadora quartz porphyry represents a volcanic vent or crater of near-surface origin, as indicated by the form of the intrusion, the abundance of breccia, and the obscurity of chilled margins. Its general similarity to the Potosi vent, which cuts late Miocene or Pliocene shales, suggests a late Tertiary age for intrusion and ore deposition at Llallagua.

The great tin deposit consists of a network of veins within and contiguous to the Salvador stock. The veins include two structural types, each sufficiently distinct to warrant different methods in exploration; and they form a lattice pattern which is broadly similar to that developed in the laboratory under progressive shearing stress.

The principal veins are marked by high-grade ore-shoots of limited vertical extent. The shoots outline a central cassiterite core which is surrounded on all sides by a low-grade sulphide shell; an expression of hypogene zoning of a unique type. The shoots are generally separated from the oxide zone by unoxidized

remnants of the sulphide shell, thus producing a vertical arrangement of zones which is incompatible with supergene enrichment.

In its geological setting and ore occurrence, Llallagua is in agreement with the near-surface zone, but in mineralogy and texture it presents many unusual features. Tourmaline and sericite occur in the wall rock, cassiterite in large part is later than bismuthinite, franckeite is earlier than the base-metal sulphides, and hypogene marcasite appears side by side with pyrite and arsenopyrite. Hard minerals follow soft minerals and those of simple composition follow the complex. The franckeite was replaced by pyrrhotite, the pyrrhotite itself was almost completely eliminated, and the ores abound in pseudomorphic patterns.

The cassiterite is uniformly of early age, preceding the base-metal sulphides, and there is no evidence of a supergene deposition. A little may exist as an oxidizing alteration of franckeite and stannite, but it is of no commercial importance whatever; hypogene cassiterite is the ore-mineral from the deepest mine level to the surface.

The complex mineralization of Llallagua cannot be correlated with the hypothermal tin deposits in granite; it reflects continued deposition through an extreme range in temperature, pressure, and chemical composition, and not the usual sequence of events. The story is one of marked decrease in the intensity of mineralization, and, in the end, an approach toward the acid fumarole and hot spring stage, which so commonly terminates the magmatic cycle at the surface.

In conclusion, Llallagua possesses many of the characteristics of near-surface deposition although it includes an abundance of high-temperature minerals. It thus constitutes an excellent example of the high-temperature deposits of the near-surface, volcanic environment; a group of restricted distribution, and one which has not received adequate treatment in the literature. To assume that within a volcanic region high temperatures cannot prevail at the depth of "near-surface" mineralization, would tend to nullify the large body of field data regarding the zonal distribution of minerals, and it would compel the belief that mineralogy is not a safe guide to temperature.

ACKNOWLEDGMENTS.

First of all, I want to thank the members of the geological and operating departments at Llallagua for their assistance and cooperation in the field; and the Board of Directors for their permission to publish the results of the investigation.

To the members of the Geological Department of Harvard University, I am grateful for advice and criticism; especially to Prof. D. H. McLaughlin, whose intimate knowledge of the ore deposits of Peru has made his suggestions of particular value. To Prof. L. C. Graton, who visited me in the field and under whose direction the laboratory work and the writing were carried out, I am under the deepest obligation for continued interest and counsel.

I also wish to acknowledge the grant of the Emmons Memorial Fellowship, which made possible the laboratory investigation of the ores; and of the John R. Finlay fund of Harvard University, which enabled me to study certain ore deposits of the Western United States, to which Llallagua offers some analogies.

The photomicrographs are largely the result of the expert guidance of Dr. H. J. Fraser and Mr. E. B. Dane, Jr., research associates of Harvard University.

SIGLO XX,
LLALLAGUA, BOLIVIA.

DISCUSSION AND COMMUNICATIONS

OCCURRENCE OF ORE IN THE WESTERN UNITED STATES.[1]

Sir:—The influence of the physical nature of the channel of circulation on the type of ore deposit has long been recognized, but its importance and some of its effects are stressed in this paper [1] in a way that will undoubtedly lead to much profitable review of past studies. It offers a good explanation of the dumping of values often observed at wide spots in a vein and at points of passage of the vein from one formation to another. However, it must not be forgotten, as pointed out by the authors, that this happened because the change in the nature of the channel caused a sudden drop in temperature, which was the direct cause of the precipitation of the values from solution. In other words, the physical nature of the channel of circulation must be studied to determine what its effect may have been on maintaining or lowering the temperature of the solutions traveling through it. This still leaves temperature as the major controlling factor in ore deposition.

They are also correct in the statement that zoning effects must always be related back to the main channel of circulation. For these effects take place laterally as well as vertically from that channel.

The statement on page 568:

> In Cananea, a similar revision of guides can be seen, for the great richness of the Colorado pipe has turned exploration from scattered, shallow, low-grade, to compact, deep, high-grade ore bodies. This pipe and others somewhat similar have aroused the expectation in other dis-

[1] Locke, Augustus, Billingsley, Paul, and Schmitt, Harrison: Some Ideas on the Occurrence of Ore in the Western United States. ECON. GEOL., vol. 29, pp. 560–576, 1934.

tricts that disseminated bodies of copper, gold, lead, and zinc may be made to yield, below the sparse superficial metallization, a more concentrated ore at deep points of entry.

is of especial interest to me, as it reflects the conviction on which my decisions in private practice have been based for many years. As early as 1918, in a letter to Mr. Louis Cates, Manager, I asked for an opportunity to prove exactly that at the mines of the Ray Consolidated Copper Company, at Ray, Arizona, but could get no consideration of my ideas. It was then already proven there, but unrecognized.

The same idea was the basis of a statement made by me in a paper read at the February, 1923, meeting of the Institute:[2]

> There is a strong presumption that the low-grade cupriferous pyrite, from which large bodies of commercial ore have been built by processes of secondary enrichment, does not represent the bottom of commercial mineralization but lies above the zone of maximum deposition of the primary sulphides of copper.

I firmly believe that careful study of the main channels of circulation through which the ore-bearing solutions rose, and above which they spread out to form low-grade disseminated ore bodies, will lead to developments that will renew the youth of more than one such mine, just as the La Colorada discovery did for Cananea.

JOHN CARTER ANDERSON.

MAKING THIN SECTIONS: SIMPLIFIED METHOD.

Sir: One of the many difficulties facing the organizer of a geological survey in Africa, where equipment is not only difficult to obtain but also in many cases beyond the financial grant to purchase, is that of the preparation of rock sections for microscopic study.

In Southern Rhodesia, Tanganyika, and Uganda, members of the Government Surveys have trained natives to prepare sections

[2] Anderson, John Carter: Economic Application of Zonal Theory of Primary Deposition of Ores. Trans. Amer. Inst. Min. & Met. Eng., 1923, p. 25.

of first-class quality without the aid of expensive mechanical cutters; and although the grinding of a rough chip by hand is rather a long and wearisome business, the delay in the preparation of the sections is offset by the ability to employ a moderately large personnel owing to the low standard of wages.

At Nairobi, the preliminary grinding of one face and the method of attaching the chip to a slide with Canada Balsam were details soon learned by locally engaged Africans; but the greatest difficulty has been experienced in teaching them to proceed from that stage. This difficulty is being overcome, however, and we are now approaching the final stage, when our native assistants must learn to judge the thickness of the sections with the aid of a microscope. For this purpose, my laboratory assistant, Mr. F. H. N. Parry, has designed a simple but efficient piece of apparatus, and as it may be of use in other "pioneer" laboratories, I am describing it below.

A color chart was prepared in water-color and divided into the four orders. Below it is a figured scale showing the thickness of the section corresponding to the interference color given by the more easily recognized rock minerals—feldspars, quartz, etc.—and at the right-hand side appear sketches of the common forms assumed by these minerals.

A second color chart which corresponds with the top chart is revealed by a long narrow slit running centrally the full length of the apparatus. To make the comparison of colors as easy as possible, only a narrow section is exposed, an arrangement obtained by attaching a movable cover to two finger stops.

The method of use is exceedingly simple; the movable slit exposing the lower color chart is moved along until the color of a quartz or feldspar obtained under the microscope is found on the chart. A quick check may be made by noticing the color that should be given by any one of the other minerals, and the thickness of the slide is then read directly from the scale of figures.

NAIROBI, AFRICA.

R. MURRAY-HUGHES.

REVIEWS

Problems of Petroleum Geology: A Symposium. Ed. by W. E. WRATHER AND F. H. LAHEE. Pp. 1070. Amer. Assoc. Petrol. Geologists: Sidney Powers Memorial Volume. Tulsa, Oklahoma, 1934. Price, $6.00.

This book contains 43 papers by 47 authors and is a sequel to the two volumes published previously by the Association under the title of "Structure of Typical American Oil Fields."

The most elusive problems in petroleum geology concern the origin, migration and accumulation of oil and gas. The data presented here deal chiefly with these three features, and all those who read the entire book will note the substantial progress that has been made in solving these problems.

Current ideas regarding source beds are interestingly summarized by Snider. Both he and most of the geologists whose papers he reviewed believe that dark shales are the source beds. Barton, in his paper on the natural history of Gulf Coast crude oils, inclines to the view that the source of the oil lies in the present containers.

The champion of local origin is Clark, who believes that rich organic matter accumulated close to the present reservoirs and that anticlinal structure is an important factor in its accumulation. He also believes that growing anticlines cause rising strata to come within the zone where optimum conditions for the formation of petroleum are present.

The authors who describe limestone pools are almost unanimous in believing that petroleum formed practically within the reservoir. Howard describes limestone reservoirs in general, Adams those of the western part of the United States and Canada, Carman and Stout those of Ohio and Indiana, and Muir those of Mexico. Those authors who describe the fields in which sandstone reservoirs are prominent also lean strongly toward a local origin. The arguments for and against migration (both lateral and vertical) are summarized and illustrated in an excellent paper by Lahee.

The relation of accumulation to structure is discussed by many contributors and some new ideas are developed. Torrey presents a map (p. 464) which shows the producing areas in Pennsylvania in conjunction with known anticlines and synclines. The lack of correspondence leads

him to make four classifications of fields; (1) those with mixtures of water, gas, and oil; (2) those controlled by cementation and (3) by permeability; and (4) those gravitational on anticlines. His analysis of the conditions responsible for each type is illuminating. Incidentally he explains the dry sands that commonly harbor synclinal accumulations as due to the effect of natural gas. In a second article, on oil-field waters, he points out that gravitational separation is probably not effective even in coarse sandstones unless the reservoir dips at least one degree. This is illustrated by many pools in southeastern Ohio and southwestern Pennsylvania.

In general, one gets the impression from the other papers that where the structures are pronounced and show steep dips, the relation is close between the high parts of the structure and oil accumulations. Where the structures are low, the influence of differential permeability becomes more important. The importance of unconformities is particularly stressed by Levorsen, who believes, however, that their chief function is to mark the position of a wedge-shaped reservoir, and that the latter forms the real oil trap.

Several years ago it was thought that complete information on the gravities of various oils would throw some light on their origin and accumulation. For that reason the papers by Reger, Bartram, Taff, and Barton should be read by every petroleum geologist. Reger reports that the gravity of the oils of the Appalachian province increases with depth and also with age. Sandstone reservoirs in general have oil of higher gravity and with a paraffine base, whereas those from limestone reservoirs have a much lower gravity and tend toward an asphaltic base.

In California, Taff divides the fields into three groups. Perhaps the most significant are those located on "completely sealed, closed, domal structures" for in these, secondary changes due to drainage and pollution are ruled out. In the Kettleman Hills pool, gravities range from 68° at the top to 34° in the lowest sand. In the Ventura pool the range is from 56° to 29°, with the lower gravities again in the lower sands. Broken structures, on the other hand, show a range of gravities from 14° to 48° in the same sand, depending on the distance from the exposed edges of the reservoir. In the third group, where the sands are exposed and subject to drainage (McKittrick and Midway) the oils change from viscous tars at the exposed edges to naphthenes of 48° gravity down dip.

In the Gulf Coast pools, however, Barton states that the oils increase with depth and also with age. Barton believes that they begin as a heavy residuum and evolve by successive stages of naphthenic, hybrid, and intermediate character to paraffine-base oils.

Another approach to problems in origin and accumulation is through the study of water analyses. Many of these were compiled and studied by

Torrey, Case, Berger, Minor, Ginter, Coffin and Jensen. In the Appalachian province, according to Torrey, Devonian brines vary from 40,000 to 160,000 parts per million. Mississippian brines average considerably lower, and Pennsylvanian ones have about the concentration of sea water. In rather striking contrast to the waters described for the central and eastern United States are those of the Rocky Mountain region. By comparison with normal sea water (35,000 p.p.m.) Rocky Mountain fields commonly show variations from 2,000 to 8,000 p.p.m. In California Jensen reports concentrations which approach those of sea water. In composition they show less calcium, magnesium and sulphate, but more carbonate and bicarbonate.

At present these data on oil-field waters defy evaluation and can be applied only in a limited way to problems in petroleum geology. One relationship which may have significance is pointed out by Washburne (p. 835). He finds by comparison that many waters show a ratio between calcium and magnesium that is from 10 to 20 times as great as in modern sea water, whereas the ratio between sodium and potassium remains the same.

In addition, the reader will find a splendid summary of Trask's exhaustive research on the organic constitution of modern sediments. The article by McCoy and Keyte summarizes well the published information on origin, source beds, oil field waters, relation of source beds to reservoirs, and time of accumulation. A real treat is provided by Howell in his historical review of the structural theory; Thom's analysis of the arguments for and against the carbon-ratio theory is stimulating and informative; McCoy, in illustrating his principles by means of typical profiles of important pools, brings out new and significant data not published before.

In conclusion, it must be recorded that this book is a remarkable report of progress. The fog of obscurity that has rested on the fundamental problems of origin and accumulation is gradually lifting. Nevertheless, the tantalizing fact remains that our progress is always one lap behind that of the wild-catter. Eventually—when he finds the last pool—we shall be able to tell him how oil and gas came to be stored in the underground reservoirs where he discovered them.

W. A. Ver Wiebe.

Univ. of Wichita,
Wichita, Kansas.

Grundzüge der Geologie und Lagerstättenkunde Chiles, by Dr. J. Brüggen. Pp. viii + 362, figs. 69, pl. 3, map. Math.-naturw. Klasse der Heidelberger, Ak. der Wissenschaften. Max Weg, Leipzig, 1934. Price, 33 M.

The author has assembled in this volume all the information that has been published on the geology of Chile, together with that which he has himself accumulated during 20 years' work in the region. He discusses the stratigraphy and also the development of the topography, using the results of his physiographic studies in reaching some new conclusions as to the ages of some of the igneous rocks and the ore deposits for which Chile is noted. He describes in some detail the origin and growth of the Andes Mountains and suggests some new views as to their structural features.

There are 26 pages devoted to the description of the glaciation of the mountains, and 13 pages to a brief account of Andean volcanoes, of which there are in Chile over 1,000 extinct and more than 100 that have been active within the past 2,000 years. Vulcanism started in Triassic time with the eruption of quartz porphyries, and was followed in the Lias to Middle Cretaceous by more basic lavas, porphyrites and diabases. At the same time there were intrusions of granodiorites accompanied by gabbros and norites, which may have been deep-seated phases of the more basic effusive lavas. Activity began again in Upper Tertiary time and has continued with few interruptions until the present. The number of recent and now-active volcanic centers is, according to the author, much larger than has heretofore been recorded. The abundance of earthquakes in the Chilean district is emphasized in a summary of 20 pages. In the neighborhood of Valparaiso there are said to be on the average about 21 quakes per year, some of which are apt to be rather heavy.

About 130 pages are occupied with descriptions of ore deposits, which, however, cannot be discussed satisfactorily until more has been learned in detail of the geology of Chile. It is stated that a true knowledge of the origin of the nitrate deposits, for instance, cannot be obtained until the late Tertiary history of the district can be worked out, and that the metallic deposits connected with the batholites along the coast cannot be understood until the ages of these batholites are determined. In the author's view many of the coast batholites are young and the ore deposits associated with them are contact deposits, although heretofore no contact deposits have been thought to exist in Chile.

The author describes in detail the nitrate deposits, which he shows cannot have had an origin similar to any one of those that have been ascribed to them, although he is apparently inclined to some bacterial theory of origin. He also refers in a few pages to the saline products of playas, to sulphur, lapis lazuli, phosphates and the coals of the country. The

Mesozoic coals are comparatively well known. They are consequently dismissed by the author in a few words. The greater part of Chilean coals are associated with Lower Tertiary beds. These are given a little more attention, but only in a general way. Thirteen pages are devoted to petroleum and bituminous shales. Petroleum occurs at many places but has not yet been vigorously exploited, although a number of borings have been made near Punta Arenas, and the structure of this petroliferous district has been worked out in part by geophysical methods.

With reference to the metallic ore bodies, which are situated mainly on the eastern flanks of the coast batholites, the author argues that since the age of the coastal granites associated with the ores has been shown to be late, the views of their character must be very different from those held by earlier geologists. Among the ore bodies described, those of gold, copper, silver and iron are given major attention, but reference is made also to those of platinum, manganese and lead, and brief mention is made of zinc, molybdenum, tungsten, cinnabar, cobalt and arsenic.

The book is a welcome addition to the summaries of the geology of South American countries that have appeared within the past few years.

W. S. BAYLEY.

The Changing World of the Ice Age. By R. A. DALY. Pp. 271, figs. 149. Yale University Press, New Haven, Dec., 1934. Price, $5.00.

This noteworthy volume from the facile pen of Professor Daly and graciously dedicated to Joseph Barrell, represents an expanded form of the Silliman lectures delivered at Yale University by the author in 1934. It is a worthy successor to an illustrious series of volumes that have emanated from his distinguished predecessors in this lecture course. It presents to the reader, with a minimum of technical terms, a vision of the ice-covered portions of North America and Europe and the effect of these ice masses upon the changing sea level, the supporting earth crust, and the resulting coastal forms. The recoil of the land masses after the removal of the depressing weight of ice is considered in detail. The changes of drainage and land and sea areas are presented clearly to the reader. Much scattered information is here concisely assembled and many new data are added. Excellent diagrams aid the reader in understanding the formation of great temporary lakes, of the mighty rivers of that time, of shore-line features and submarine banks. Naturally, consideration is given to the glacial-control theory of coral-reef formation. The chief headings are Ice Caps, Past and Present, Recession of the Fennoscandian Ice, Recession of the North American Ice, Mechanism of the Earth's Deformation and Recoil, High and Low Sea Levels of the Pleistocene, and Coral Reefs of the Ice Age.

It is a book I heartily recommend to all who are interested in geology.

ALAN BATEMAN.

The Brown Iron Ores of the Western Highland River, Tennessee. ERNEST F. BURCHARD AND OTHERS. Pp. 236, pls. 33, figs. 21. Tenn. Dept. of Education, Div. of Geology, Bull. 39. Nashville, 1934.

A general account of the brown iron-ore deposits of the highland region in the Tennessee River valley in west-middle Tennessee. The ore is in lumps, veins, etc., in the residual clay and chert debris overlying deeply weathered horizontal cherty limestones of Mississippian age, in pockets containing a few hundred tons of ore and in groups of pockets, some of which have yielded over a million tons by means of steam-shovel stripping and mining. The source of the iron oxide, which was formed mainly in Tertiary time, is believed to have been glauconitic beds that formerly overlaid the region. The report consists largely of descriptions of individual deposits.

W. S. BAYLEY.

The Stone Industries. By OLIVER BOWLES. Pp. 519, figs. 73. McGraw-Hill Book Co., New York, 1934. Price, $5.00.

This book fills a long-felt need in technical literature, existing books on this subject being out of date and insufficient in technical data. The author's extended experience as quarry specialist for the U. S. Bureau of Mines has provided him with abundant observations and first-hand knowledge of his subject. Consequently the book is replete with detail.

The four chapters of Part I, General Features, deal with Extent and Subdivision, Minerals and Rocks, Factors governing Rock Utilization, and Prospecting and Development. Part II, Dimension Stone, has eleven chapters dealing respectively with General Features, Limestone, Sandstone, Granite, Marble, Slate, Soapstone, Boulders as Building Material, Foreign Stones, Miscellaneous Rocks and Minerals, and Deterioration, Preservation and Cleaning of Stonework. Part III, Crushed and Broken Stone, deals with General Features, Limestone, and Other Crushed Stones.

The volume is illustrated by drawings, charts, and mediocre halftones. Little geological information is available but there are abundant technological data that will prove of value to those interested in the stone industries.

Copies of books mentioned under "Reviews" or under our "New Book List" (see advertisement page) may be purchased through our Journal Bookshop by writing to W. S. Bayley, University of Illinois, Urbana, Ill.

BOOKS RECEIVED.

DAVID GALLAGHER.

Deutsches Bergbau Jahrbuch, 1935. H. HIRZ AND W. POTHMANN. Pp. 358. Wilhelm Knapp, Halle (Saale), 1935.

Die Grundwasserverhältnisse des Kantons Zürich. J. HUG AND A. BEILICK. Pp. 328, figs. and pls. 134, map. Beiträge zur Geologie der Schweiz, Geotech. Serie, Hydrologie, Lief. 1. Comm. Geotech., Soc. Helv. des Sci. Nat., Bern, 1934. Detailed and voluminous treatise on groundwater; well published; well illustrated.

Introduction aux Études Minières Coloniales. Pp. 349, figs. 25, pls. 9. Bureau d'Études Géologiques et Minières Coloniales, Paris, 1934. Essentially a textbook in twelve chapters by twelve of the best French authorities on various phases of geology; including such subjects as types of ore deposits, surface alteration of rocks in the tropics, alluvium, geophysics, microscopy of coal, metallographic microscope technique, etc.

Comité d'Études Minières pour la France d'Outre-Mer, Annuaire, 1934. Pp. 428. Catalog of colonial mines, mineral legislation, production, etc. Paris, 1934.

Kohle und Eisen im Weltkriege und in den Friedensschlüssen. F. FRIEDENSBURG. Pp. 332, figs. 13. R. Oldenbourg, München und Berlin, 1934. How coal and iron influence the political destiny of nations, together with important material on the Saar question.

Quebec Bureau of Mines, Annual Report 1933, Part A. Pp. 175, figs. 3, pls. 9. Mining Operations and Statistics. **Part B.** Pp. 80, figs. 4, pls. 5, map in color. Senneterre Map-Area, Abitibi District, by L. V. BELL AND A. M. BELL. Quebec, 1934.

Canada Department Mines, Geological Survey, Summary Report 1933, Part B. Pp. 176. Ottawa, 1934. Contains: Michel Coal Area, B. C., and Coleman South Coal Area, Alberta, B. R. MacKay; Buff and White-Burning Clays of Southern Saskatchewan, F. H. McLearn and J. F. McMahon; Paleozoic and Jurassic Formations in Well Sections in Manitoba, R. T. D. Wickenden; Deep Borings in the Prairie Provinces, W. A. Johnston.

Ontario Department Mines, 43d Annual Report, Part I, 1934. Pp. 153. Mineral statistics, catalog of mines, etc., for 1934, by several authors. Toronto, 1935. **Part IV.** Pp. 32. Geology of the Straw-Manitou Lakes Area. J. E. Thomson. Geologic map in color. Toronto, 1934.

Report of the Planning Committee for Mineral Policy, National Resources Board, Part IV. National Planning and Public Works in Relation to National Resources, including Land Use and Water Resources, with Finding and Recommendations. Pp. 59. Superintendent of Documents, Washington, D. C. 15 cts.

Geologic History at a Glance. L. W. RICHARDS AND G. L. RICHARDS, JR. Stanford University Press, Calif. The title itself is an adequate review; as much of the subject as is humanly possible has been presented in two large diagrams in which extraordinarily fine photographs are ingeniously explained by diagrammatic and tabular notes.

Cummingtonite in the Limestones of Kudurekanave, Mysore State, India. B. RAMA RAO. Pp. 36, figs. 1, pls. 6, map in color. Mysore Geol. Dep't., Bull. 15. Bangalore, 1934.

Saragura and Associated Gold Occurrences of the Mwanza Area. F. B. WADE AND F. OATES. Pp. 44, map in color. Tanganyika Geol. Surv., Short Paper No. 12. Dar es Salaam, 1934. General geology, economic geology, and petrography.

Asbestos in the Ceded District of the Madras Presidency; with Notes on Its Occurrence in Other Parts of India. A. L. COULSON. Pp. 123, pls. 5, map. India Geol. Surv. Mem. vol. LXIV, Pt. 2. Calcutta, 1934. Rs. 3–8 or 6s.

The Dhubri Earthquake of the 3d July, 1930. E. R. GEE. Pp. 106, pls. 11. India Geol. Surv. Mem. vol. LXV, Pt. 1. Calcutta, 1934. Rs. 4–6 or 7/3.

Geology of the Krol Belt. J. B. AUDEN. Pp. 97, pls. 8. Crush Conglomerates of Dharwar Age from Chota Nagpur and Jubbulpore. M. S. KRISHNAN. Pp. 8, pls. 3. India Geol. Surv. Records, vol. LXVII, Pt. 4. Calcutta, 1934. Rs. 2–12 or 5s.

General Report, Geological Survey of India for 1933. L. L. FERMOR. Pp. 104. India Geol. Surv. Records, vol. LXVIII, Pt. 1. Calcutta, 1934. Rs. 2–12 or 5s. Also three short papers.

Tanganyika Geol. Surv., Annual Report, 1933. E. O. TEALE. Pp. 60, guide map. Dar-es-Salaam, 1934. 2/5s. Brief account of activity and geological findings.

Marble Prospects in Giles County, Virginia. A. A. L. MATHEWS. Pp. 52, pls. 9, figs. 7, tables 3. Virginia Geol. Surv. Bull. 40. University, Va., 1934. Petrography by A. A. Pegau.

Fisiografia e Geologia da Güiana Brasileira. P. MOURA. Pp. 109, pls. 88, maps 2. Instituto Geól. e Min. do Brasil, Bol. 65. Rio de Janeiro, 1934.

Bergmännische Grundwasser Untersuchungen. H. MATSCHAK. Pp. 105, figs. 20. Wilhelm Knapp, Halle (Saale), 1934. Especially concerning brown-coal mines.

Underground Water Resources of Kenya Colony. H. L. SIKES. Pp. 40, pls. 21. Crown Agents for the Colonies, Westminster, S. W. 1, 1934. 5/.

Provincia Magmatica do Brasil Meridional. D. GUIMARÃES. Pp. 78, pls. 6. Instituto Géol. e Min. do Brasil, Bol. 64. Rio de Janeiro, 1933.

SOCIETY OF ECONOMIC GEOLOGISTS

The annual meeting of the Society was held jointly with the American Institute of Mining and Metallurgical Engineers in New York on February 21. The papers of both societies were presented, some to appear in the Institute proceedings, others in this journal. The list follows: (1) The Bajada Placers of the Arid Southwest—B. N. Webber; (2) Hog Mountain Gold District, Ala.—C. F. Park, Jr.; (3) Veins and Faults in the Bralorne Mine—Ira B. Joralemon; (4) Outstanding Structural Relations of Quebec Gold Deposits—J. E. Gill; (5) Distribution of Silver in Base-metal Ores—S. G. Lasky; (6) Supergene Sphalerite, Galena and Willemite at Balmat, N. Y.; (7) Quicksilver Deposits near Little Missouri River, Ark.—J. C. Reed and J. M. Hansell; (8) Geology of Parker Hill Cinnabar Mine, Pike Co., Ark.—N. H. Stearn; (9) Geology of the Tungsten Deposit at Silver Dyke, Nev.—P. F. Kerr; (10) The Magnetite Deposit near Humacao, Puerto Rico—R. J. Colony and H. A. Meyerhoff; Absorption, Permeability and Metasomatism of Limestone—G. W. Bain; Origin of Certain Systems of Ore-bearing Fractures—W. H. Emmons; Origin and Economic Importance of Bedding Plane Movements—C. H. Behre; Genesis of the Gulf Border Sulphur Deposits—L. S. Brown; Bedding Replacement Deposits of the Cave-in-Rock Fluorspar District, Ill.—L. W. Currier; Research on Ore Deposition: Discussion.

The sessions were largely attended, and spirited discussion took place. In the evening a banquet was held at the Princeton Club, at which W. E. Wrather delivered the Presidential address and the Penrose Gold Medal was presented by W. O. Hotchkiss to the recipient, C. K. Leith, who made a reply.

The thanks of the Society are due to W. B. Heroy, for his efficient handling of the program and arrangements.

The election of officers was announced as follows: *President for 1936,* D. F. Hewett; *vice-president,* J. W. Finch; *councillors for 1935–6,* G. M. Fowler, D. C. Barton, E. F. Burchard; *regional vice-presidents for 1935, Africa,* L. Reinecke; *Asia,* Takeo Kato; *Australia,* L. K. Ward; *Europe,* R. H. Rastall; *North America,* J. B. Tyrrell; *South America,* W. F. Walker.

The following new members were declared elected: P. F. Armstrong, Olof Baeckström, G. A. Bétier, G. W. Grabham, H. S. McQueen, N. H. Magnusson, R. W. Smith, E. D. Wilson, Shinji Yamane.

SCIENTIFIC NOTES AND NEWS

W. L. Whitehead, of the Massachusetts Institute of Technology, has been examining mines in Cuba, and later visited California and Utah.

Sydney H. Ball, of Rogers, Mayer & Ball, New York City, has lately been in the West on professional business.

R. W. Brock, of the University of British Columbia, has been appointed chairman of the Vancouver Harbor Board.

H. Ries, of Cornell University, delivered the Orton Memorial lecture at the annual convention of the American Ceramic Society, on the subject of Geology in Clay Research.

Ira B. Joralemon has been appointed by the Federal Court as adjudicator of claims between Consolidated Coppermines and Nevada Consolidated Copper Company, following recent litigation.

Leopold Reinecke, of Johannesburg, South Africa, is seriously ill and has gone to London for treatment. Mr. Pelletier is attending to his work.

T. W. Gevers, of the Geological Survey, Union of South Africa, has been appointed to the chair of Geology and Mineralogy in the University of the Witwatersrand, succeeding Robert B. Young, retired.

Hugh M. Roberts, of Duluth, Minnesota, has been spending some time in Mexico in the interests of the Cusi Mexicana Mining Company.

George C. Heikes, who has been for several years in Poland as mining geologist for the Anaconda Copper Company subsidiary there, has returned to this country and is living in Westfield, New Jersey.

G. G. Dobbs has returned to London after an exploring expedition in Nova Scotia for Consolidated Goldfields of South Africa.

M. F. Fairlie is now managing director of McKenzie Red Lake, in which his company, Mining Corporation of Canada, has a large interest.

William C. McKinley, of Peoria, Illinois, is collecting data and samples for tests of American amber, and desires contributions of material.

Arthur L. Day addressed the Washington Academy of Science at its January meeting on "Public Safety in Earthquake Regions." At the March meeting Charles A. Edwards gave an address on "Science, Education, and Industry; Whither Drifting?"

Olaf Andersen, of the U. S. Steel Research Laboratory, Kearney, N. J., recently gave a series of nine lectures at Princeton University on Phase Equilibrium Diagrams of the Refractory Oxides; their interpretation and application to slags, refractories, and igneous rocks.

The annual meeting of the Section of Volcanology of the American Geophysical Union will be held April 25 and 26, 1935, in the National Academy Research Council Building, Washington, D. C. Papers dealing with any phase of igneous phenomena or their products can be submitted to the Secretary, A. H. Koschmann, U. S. Geological Survey, not later than March 15.

The National Research Council announces that applications for grants-in-aid for 1935 must be sent to the Secretary, C. J. West, before April 1. The following grants have already been made: K. E. Caster (Cornell): Stratigraphy and Paleontology of the Pocono Formation of Pennsylvania; Maurice Ewing and A. P. Crary (Lehigh): Geophysical Investigation; F. F. Grout (Minnesota): Mechanics of Igneous Action; E. H. Johnson (Texas): Physical and Economic Characteristics of the Natural Regions of the Gulf Southwest; G. W. Rust (Chicago): Studies of a Newly Discovered Center of Ancient Volcanic Activity in Southeastern Missouri; J. R. Whitaker (Wisconsin): Regional Geography of Southern Ontario.

The Congrès International des Mines, de la Métallurgie et de la Géologie Appliquée will hold its seventh session in Paris October 20 to 26, 1935. The economic geology section will hold sessions on the following subjects: Magmatic and sedimentary deposits, petroleum, geophysics, engineering and agricultural geology, hydrology and hot mineralizing solutions, economic minerals, and research organizations. International attendance is desired, and membership blanks and circulars may be obtained from F. Blondel, 13 rue de Bourgogne, Paris VIIme. Papers may also be submitted to him.

The Seventeenth International Geological Congress, to be held in Russia in 1937, is announced in a preliminary statement in Russian. The topics contemplated are: (1) World resources of coal and petroleum; (2) Pre-Cambrian and its mineral deposits; (3) The Permian; (4) Mesozoic stratigraphy; (5) Magmatic processes; (6) Structure of Asia; (7) Gravity anomalies; (8) History of geologic knowledge. The tentative excursions are: A–1, Northern—Pre-Cambrian and minerals (to Kola Peninsula), 15 days. A–2, Urals—Structure, stratigraphy, coal, and mining, 22 days. A–3, Southern—Iron, coal, salt, Carboniferous and Mesozoic, 20 days. A–4, Volga—Mesozoic, Quaternary, engineering geology, 18 days. C–1, Urals, Baku, etc.—Petroleum and stratigraphy, 50 days. C–2, Central Asia—Stratigraphy, structure, volcanism, mineral deposits (Turkestan, Pamit Mountains, etc.), 50 days. C–3, Transcontinental—Stratigraphy, structure, ore deposits, of Urals, Transbaikalia, and Far East, 40 days. C–4, Turkestan, Siberia—Geology and ore deposits of Urals, Altai, and eastern Kazakstan, 40 days.

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